Investigation of peatland restoration (grip blocking) techniques to achieve best outcomes for methane and greenhouse gas emissions/balance. Controlled Environment (Mesocosm) Experiment. Final Report to Defra. Project code SP1202

Other

Investigation of peatland restoration (grip blocking) techniques to achieve best outcomes for methane and greenhouse gas emissions/balance.

Controlled Environment (Mesocosm) Experiment Final Report

Defra Project SP1202

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1. Aim, objectives, and background

1.1 Project aim and objectives

The overall aim of project SP1202 is to **review restoration methods used in blanket peatlands and to identify, using laboratory and field experiments, those methods which produce the best outcomes in terms of reducing peatland methane (CH_4) emissions and global warming potential (GWP).** Overall, the project has four main objectives:

(a) To undertake a literature review of the materials and methods for grip blocking and peatland restoration currently in use in the UK and the impacts of the techniques on green-house gas (GHG) emissions.

(b) To undertake controlled, small-scale laboratory experiments to examine how different grip blocking techniques might affect GHG emissions from restored blanket peatland.

(c) To conduct larger-scale field trials of different grip blocking methods to see how these affect GHG emissions from restored blanket peatland.

(d) To report the results of (a) to (c) in a format that can be easily understood by site managers and also in the international scientific literature.

This report deals with part (b) and presents the results and conclusions of the small-scale/laboratory mesocosm experiments carried out at the Open University. It should be noted that, for brevity, we have kept referencing to a minimum in this report. A full literature review is given in **Baird *et al*. (2009)** and in updates produced for the current project (SP1202; available on request from the project leader: Prof. Andy Baird; a.j.baird@leeds.ac.uk). The findings from the experiments are also being prepared for publication as papers in international academic journals, and these will contain more detailed referencing.

Restoration of damaged peatlands is promoted as a means of restarting their carbon (C)-sink function. However, until recently, CH_4 emissions have not been considered when estimating the benefits arising from restoration (**Baird *et al*., 2009**). CH_4 has largely been ignored when compiling C inventories because it represents a relatively small proportion – often much less than 10% in mass terms – of the total C budget of peatlands (*cf*. **Baird *et al*., 2009**; **Thompson, 2008**). However, CH_4 is a much more potent GHG than CO_2, having a GWP 25 times that of CO_2 over a 100 year time frame (**Forster *et al*., 2007**). This means that any increase in CH_4 emissions as a consequence of restoration could have a disproportionate effect on the GWP of the peatland, thus potentially reducing or even negating the benefits of peatland restoration.

In the UK, drain or 'grip' blocking has been employed as a peatland restoration method since the 1980s. More than 150 peatland restoration projects are currently ongoing in the UK (**Baird *et al*., 2009**), often with the aim of restoring ecological and hydrological function, but increasingly with the aim of restoring peatland C-sink function. A range of damming and infill materials have been used, including peat turves, plastic piles, wooden planks/plywood, heather bales, straw bales and stone (**Armstrong *et al*., 2009**).

Peatland restoration leads to higher (closer to the surface) water tables, so that the thickness of the aerobic layer is reduced, which should lead to a reduction in overall rates of peat decomposition (rates of aerobic decomposition above the water table are much higher than rates of anaerobic or anoxic decomposition below the water table). In consequence, restoration should lead to less CO_2 release to the atmosphere. Depending on how higher water tables affect plant productivity, restoration may even lead to a net uptake of CO_2, which, depending on fluvial losses of C, may indicate net peat accumulation (a C sink). However, higher water tables increase the thickness of the zone in which CH_4 may be produced (methanogenesis) and reduce the thickness of that part of the peat profile in which oxidising bacteria can consume CH_4 (methanotropy) (*cf*. **Baird *et al*., 2009**). Therefore, we might expect there to be increases in peatland CH_4 emissions following restoration. The exact change to CH_4 emissions and the effect of restoration on the C-sink function of peatlands are likely to depend on the restoration method employed and the plant functional types (PFTs) growing on/in the peatland.

Given this context, **the small-scale controlled laboratory experiments had the following objectives**:

(a) To provide interim results that could inform the design of the field trials (objective (c) – see above).
(b) To provide information that can be used to identify restoration methods yielding the lowest GWP.

This report concentrates on the second objective.

The laboratory mesocosm experiments investigated GHG exchanges from both **grips** (whether infilled or dammed with pools) and from areas between the grips (**inter-grip areas**), the latter experiencing a higher water-table as a result of restoration. Although the focus of the project is on CH_4, it was also necessary to consider net CO_2 emissions (net ecosystem exchange [NEE], with CO_2 fluxes weighted for daylight and night-time conditions) and emissions of nitrous oxide (N_2O) so that the GWP of different restoration operations was properly calculated. As well as measuring GHG fluxes between the peatland and the atmosphere, we looked at pore-water [CH_4] (square brackets denote concentration), pore-water [cations], pore-water [anions], pore-water [acetate], and dissolved organic carbon (DOC) content of pore water.

The controlled laboratory study involved two distinct experiments, dealing with GHG emissions from grips (Experiment 1) and from inter-grip areas (Experiment 2) (see the next two sections). Damming or the infilling of grips can be expected to alter both average wetness (water level/table in grips, water table between grips) and **water-level regime**; hence, we included the latter in our experimental design. Future management of the upland blanket peatland resource will likely be affected by **climate change**, particularly increases in temperature, so we also looked at GHG emissions under higher temperatures. Finally, we considered how CH_4 emissions from restored blanket peatland might be reduced or mitigated by sulphate additions or 'amendments'. To provide focus to our experiments, we tested nine hypotheses. Each hypothesis is stated below, together with a brief explanation of why the hypothesis was posed. All features of the experimental work at the Open University were approved in advance by Defra and the project's Steering Group (details of the membership of the group can be provided separately by the project leader: Prof. Andy Baird; a.j.baird@leeds.ac.uk).

1.2 Experiment 1

This experiment focused on GHG exchanges from the **grip or blocked grip channel** and evaluated the effects of restoration method, water-table dynamics and climate on CH_4 emissions and GWP. Five hypotheses were tested, as described below.

1.2.1 Effect of restoration method (infill) on blocked/dammed grip CH_4 emissions

Hypothesis 1: CH_4 emissions will differ according to the grip blocking method.
Rationale: It is thought that CH_4 emissions will differ according to the grip blocking method. The differences are likely to occur as a result of differences in the type and quality of the infill material (e.g. C to N ratio) which will influence the substrate supply to methanogens, and therefore CH_4 production and emission rates. The nature of the infill may also affect methanotrophy and thereby CH_4 emissions. **Frenzel and Karofeld (2000)** suggested that the zone 4-6 cm below the capitula (the rosette of branches and leaves uppermost on a *Sphagnum* stem) in carpets or mats of *Sphagnum cuspidatum* Ehrh. ex Hoffm.(Feathery Bog-moss[1]) may be intensely oxidising and may lead to a high proportion (close to 100 %) of the CH_4 produced deeper in the peat profile being oxidised as it moves upwards through the peat. Therefore, grips with pools behind dams that have been colonised by *S. cuspidatum* may have lower rates of emission than grips blocked with, for example, heather bales. So-called 're-profiling', which involves using peat and vegetation in inter-grip areas to partially fill or block a grip, may also provide a flush of labile substrates for methanogens, therefore increasing CH_4 production.

[1] The Sphagna do not have traditional common names like other peatland plants such as heather and cotton grass. Usually, they are referred to by their botanical (Latin) names. However, recently, English names have been coined for the Sphagna and they are given in this report. The names used here are taken from **Atherton *et al*. (2010)**.

1.2.2 Effect of water level (WL1: high and static; WL2: fluctuating) on GHG emissions

Both static and fluctuating water levels were considered so that we captured a range of possible hydrological regimes in restored sites. The degree to which water levels vary in the field will depend on a range of factors such as the part of a hillslope occupied by blocked grips, grip spacing, dam spacing, type of infill (if any), rainfall, and evaporation. Most blocked grips will experience periods when water levels are stable and periods when they fluctuate. Water level and water-level regime were the subject of three hypotheses as follows.

Hypothesis 2: A high and static water table promotes CH_4 emissions.
Rationale: It has been well documented that water-table level influences CH_4 emissions from peatlands (*cf*. **Baird *et al*., 2009**). In Experiment 1 two water-level regimes were considered (WL1: high and static; WL2: fluctuating) and their influence on emissions assessed. A high and static water-table might be expected to promote greater fluxes of CH_4 to the atmosphere because it results in a thicker zone of potential methanogenesis and a smaller zone of methanotrophy (**Baird *et al*., 2009**).

Hypothesis 3: A fluctuating water-table reduces CH_4 emissions.
Rationale: If the water-table regularly falls by 10 cm or more below the top of the blocked grip, the infill material is periodically oxidised, thus reducing rates of methanogenesis (which in peat appears to be strictly anaerobic) and increasing rates of methanotrophy. Previous studies have illustrated that drought decreases CH_4 emissions from wetlands (e.g., **Moore and Knowles, 1989**; **Freeman *et al*., 1993**; **Moore and Roulet, 1993**).

Hypothesis 4: A fluctuating water-table is likely to increase N_2O emissions.
Rationale: N_2O production and emission are dependent on both the supply of available N (NO_3^-) for denitrification (i.e., the N-richness of the infill used), substrate supply (available C), alternative terminal electron acceptors, and the hydrological regime which influences redox potential (**Silvan *et al*., 2005**). A fluctuating water table and limited substrate supply provide the ideal situation for incomplete denitrification and N_2O production to take place. However the N status of the infill material is likely to be low given the low nutrient status of blanket peatlands, so N_2O production may be low regardless of hydrological regime.

1.2.3 Effect of climate on CH_4 emissions

Hypothesis 5: A warmer climate will lead to higher rates of CH_4 emission.
Rationale: A warmer climate leads to higher rates of CH_4 production and, therefore, higher rates of CH_4 emission. Methanogenesis has been shown to be highly temperature-sensitive, increasing exponentially with temperature in the ranges of temperature commonly experienced in nature (e.g. **Dunfield *et al*., 1993**). Even under conditions of a fluctuating water table, we might expect CH_4 emissions to increase under a warmer climate. This is because CH_4 production appears to be more temperature-sensitive than methanotrophy (**Dunfield *et al*., 1993**). Therefore, CH_4 production increases proportionately more than CH_4 oxidation under a higher-temperature climate.

1.3 Experiment 2

In Experiment 2 the role of restoration and plant functional type (PFT) in controlling CH_4 emissions from restored peat outside of the grip – i.e., between grip channels in the **inter-grip area** – were examined. In the experiment we made the assumption that the various infill / grip blocking methods had the same effect on water levels in the inter-grip zone. Consideration was also given in Experiment 2 to the effect of sulphur amendments (no amendment versus an application of 100 kg S ha^{-1} y^{-1}) as a means of reducing CH_4 emissions.

1.3.1 Effect of vegetation on CH_4 emissions from inter-grip areas

PFT effects were tested with one hypothesis.

Hypothesis 6: Different plant functional types will be associated with different fluxes of CH_4.
Rationale: Different PFTs produce litter (and in some cases root exudates) at different rates (~plant productivity) and with different levels of decomposability, which might be expected to cause differences in the amount of CH_4 being produced and emitted. PFT may also affect how CH_4 is transported through peat to the atmosphere. Sedges, for example, seem to be associated with higher rates of CH_4 emission (compared to areas without sedges and dominated by *Sphagnum*; e.g., **Green and Baird, in press**). Possible reasons for this suggestion include: (i) sedges act as gas conduits, such that CH_4 moves through the aerenchyma[2] of the plants by-passing methanotrophic 'processing' in the peat profile; and (ii) exudates from sedge roots act as readily-available substrate for methanogens, thus increasing rates of CH_4 production but also, possibly, enhancing the breakdown of litter and peat in the vicinity of the roots (through an additive effect). The different PTFs compared in Experiment 2 were: terrestrial *Sphagnum* (*Sphagnum papillosum* Lindb. – Papillose Bog-moss), sedge (*Eriophorum vaginatum* L. – Hare's Tail Cotton Grass), and ericaceous shrub (*Calluna vulgaris* (L.) Hull. – Common Heather).

1.3.2 Effect of sulphur addition on CH_4 emissions

Hypothesis 7: Sulphate additions will reduce CH_4 fluxes.
Rationale: Sulphate additions are known to reduce CH_4 emissions (e.g., **Gauci *et al*., 2002, 2004a, 2005, 2006**). Sulphate stimulates competitive interactions with microorganisms (sulphate-reducing bacteria – SRB) that are energetically superior to methanogens, thus leading to lower CH_4 fluxes where biologically-available C substrates are limiting (as is the case in peatlands).

Hypothesis 8: Warmer conditions will favour CH_4 production and reduce the effect of sulphate additions.
Rationale: The effect of sulphate on CH_4 emissions appears to be dependent on climate; specifically, the effect of S additions on reducing CH_4 emissions seems to be more pronounced in cooler conditions (**Gauci *et al*., 2004b**). In rain-fed (ombrotrophic) bogs methanogenesis occurs as a result of two processes – H_2/CO_2 reduction and aceticlastic (acetate-utilising) methanogenesis – roughly in a proportion of 2:1. Methanogenesis via H_2/CO_2 reduction is readily out-competed by SRB at all temperatures; however, competition for acetate is known to be temperature-sensitive, with cooler temperatures favouring sulphate reduction and warmer temperatures tipping the balance in favour of CH_4 production.

1.3.3 Effect of climate on CH_4 emissions

Hypothesis 9: A warmer climate will lead to higher rates of CH_4 emission.
Rationale: A warmer climate may lead to higher rates of CH_4 production and, therefore, higher rates of CH_4 emissions (as outlined in the rationale for Hypothesis 5).

2. Materials and methods

2.1 Field site

The description that follows is based closely on **JNCC (2003)**. The Migneint-Arengi-Dduallt is situated within Snowdonia National Park in Wales (52° 58' 38'' N, 03° 46' 56'' W), and is a Special Area of Conservation (SAC). Of the 200 km^2 expanse of the Migneint-Arengi-Dduallt, 51.9% comprises bogs, marshes or fen (**JNCC, 2003**). Using the National Vegetation Classification (NVC), much of the peatland areas is classed as *Sphagnum*-rich M19 *Calluna vulgaris – Eriophorum vaginatum* blanket bog, although M18 *Erica tetralix – Sphagnum papillosum* blanket bog is also widespread. The Migneint has been degraded by drainage (gripping), burning, over-grazing and, in places, afforestation. It has also been affected by atmospheric sulphur and nitrogen deposition leading to soil and water acidification. Despite such negative impacts, the peatland plant assemblage remains relatively intact in many places. Maps compiled by the Countryside Council for Wales (CCW) from aerial photography shows that the vast majority of the area has been affected by artificial drainage, with different areas gripped from the 1930s to the 1970s.

[2] Inter-cellular spaces in the roots, shoots, and leaves of plants, that provide channels for the transport of gases between the shoots and roots (**Rydin and Jeglum, 2006**).

2.2 Sample collection and laboratory incubations

Sixty-three intact peat cores or mesocosms for the two experiments were collected from the field site in May 2010 in an area close to where the field trials are taking place (see (c) in section 1.1). Two sampling protocols were used depending on the experiment for which the cores were collected. For Experiment 1, open-ended 11-cm diameter, 50-cm deep polyvinyl chloride (PVC) cylinders were inserted into bare peat at the base of a grip to a depth of 25 cm. These were tamped into place using a rubber mallet. For Experiment 2, open-ended 11 cm diameter, 50 cm deep PVC cylinders were inserted into the peat using the scissor-cut-extraction protocol outlined in **Green and Baird (in review)** (Figure 2.1). The samples in the PVC cylinders were wrapped in tight-fitting and waterproof plastic bags to maintain the water table level at the time of sampling and to prevent drainage losses. Vegetation within the mesocosms (mosses and vascular plants) remained intact throughout the sample collection and subsequent incubations, although some damage must inevitably have occurred to roots during the cutting of the peat and insertion of the cylinders. We checked for any damage by monitoring the vegetation in each sample throughout the experiments. In all vegetated mesocosms, there was little evidence of reduced rates of growth or dieback. For example, in all of the Experiment 2 samples containing *C. vulgaris* (see section 2.3 and Table 2.3 below), growth of the shrub occurred (see Figure 2.1, right picture).

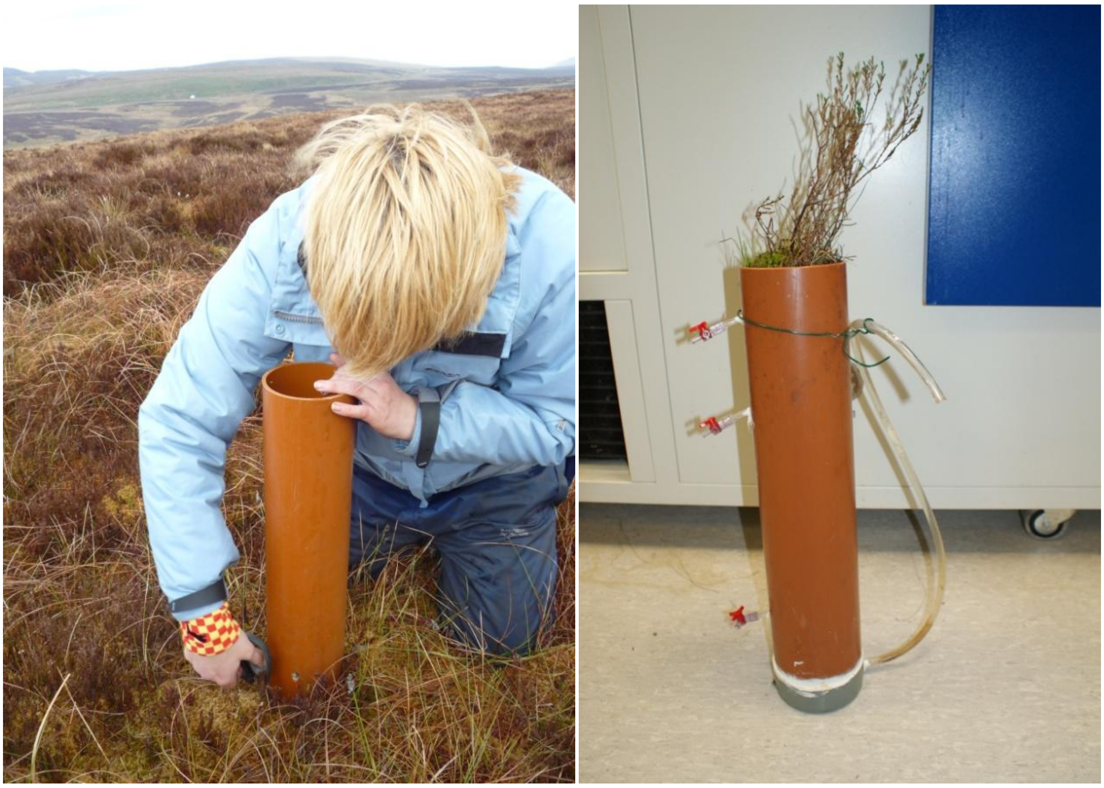

Figure 2.1. *The sampling technique (left) and sample holders (right) used in the controlled-environment study. Photographs: Carl Boardman/Sophie Green.*

Within a few hours of collection, the PVC holders were capped at the base and fitted with pore-water sampling ports (at depths of 5, 15 and 40 cm) (Figure 2.1). The pore-water ports consisted of a three-way value attached to a 1 mL perforated syringe packed with glass wool (to provide filtration of macro particles) via tubing. The bases were fitted with over-flow tubes that allowed us to manipulate water levels within the samples (see Figure 2.1).

The peat samples were kept (incubated) within four Snijders Microclima 1750 environmental cabinets (Figure 2.2) in which 'sunlight' (photosynthetically-active radiation – PAR), temperature, and humidity could be controlled. The incubations for both experiments started on 12th July 2010 and continued for **nine months**. Three cabinets were used to replicate present-day average meteorological conditions at the field site (based on data obtained for weather stations near the field site and data from the British Atmospheric Data Centre – BADC) (Table 2.1). **For the nine-month duration of the experiment, we changed conditions in the cabinets to represent conditions from April to December**. Thus, the first setting in the cabinets was for April-time conditions, even though the real start date was July. A single cabinet was programmed to simulate a **warmer climate anticipated for the second half of this century**, by tracking the present-day conditions in the other cabinets, but with a positive temperature (2°C) offset (based on UKCIP09 projections) (Table 2.1 values plus 2°C). Three climate projections were considered for the warmer climate based on three GHG emission scenarios – low, medium and high – over seven 30-year time periods (2010-2039, 2020-2049, 2030-2059, 2040-2069, 2050-2079, 2060-2089, and 2070-2099). CL2 (the warmer climate used in our experiments) was based upon the later two periods in order to assess the longer-term (50-90 year) behaviour of restored peatland. The 2°C increase falls within four of the six climate scenarios generated for the two time periods (spanning 2060-2099). The peat samples were rotated every two weeks within the cabinets to avoid confounding block effects due to small differences in conditions between different cabinets or locations within cabinets.

Table 2.1. *Environmental cabinet set-point meteorological conditions.*

Simulated month	Diurnal phase	Atmospheric temperature (°C)	Relative humidity (%)	PAR ($\mu mol\ m^{-2}\ s^{-1}$)	Hours
April	Day	9.4	70.6	270	14
	Night	7.0	81.2	0	10
May	Day	12.7	69.1	280	15
	Night	9.8	81.2	0	9
June	Day	14.7	76.0	330	16
	Night	11.5	88.6	0	8
July	Day	15.7	78.2	340	16
	Night	13.0	89.5	0	8
August	Day	14.9	79.9	330	15
	Night	13.0	88.4	0	9
September	Day	14.7	77.9	280	13
	Night	12.5	87.1	0	11
October	Day	11.8	80.5	250	11
	Night	10.4	86.8	0	13
November	Day	8.1	80.6	200	9
	Night	7.2	83.2	0	15
December	Day	5.8	84.3	150	8
	Night	5.2	85.5	0	16

2.3 Experimental manipulations or statistical treatments

The different restoration methods, water-table regimes, climates, and sulphur amendment were combined factorially to produce 12 + 9 different treatments across the two experiments. The different combinations are given in Tables 2.2 and 2.3. As noted in section 2.2, the peat samples were held in specially-constructed cylinders or holders that allowed us to manipulate and maintain the water-table (Figure 2.1). In Experiment 1, we sought to replicate four restoration outcomes:

(a) Damming of grips to create **open-water pools** behind the dams.

(b) As for (a) but representing a situation where the pools have been colonised and in-filled by **mats of *Sphagnum***. A common *Sphagnum* species to spread across and into pools in this way is *S. cuspidatum*.

(c) Damming and **infilling of grips with heather** (*C. vulgaris*) bales.

(d) Blocking of grips using what is known as the **re-profiling** method (see also section 1.2.1). This relatively new method involves constructing peat dams (as in (a) above), but also partially infilling the grip channel between the dams with peat and vegetation from the inter-grip areas either side of the channel.

For (a)-(d) the lower part of each sample comprised 25 cm of peat sampled from the base of a grip. For (a) we assumed there was just water above this material as would occur in a pool behind a peat dam. For (b) we used *S. cuspidatum* mats (25 cm depth) collected from hollows near the field experimental area. The mats comprised the growing *Sphagnum* capitula and *Sphagnum* litter below. The mats were placed in the cylinders on top of the grip-base peat. For (c) we used heather cut from the site, of which 150 g was inserted into the cylinders above the grip-base peat. For (d) we used material collected from the uppermost section of the 'walls' of grips down-slope from the field experimental area. This material was a mix of peat and plant material and, like the heather in (b) above, was inserted into the cylinder above the grip-base peat.

Experiment 2 considered three plant functional types (Table 2.3) (see also section 1.3.1): **moss** (*Sphagnum*), **sedge** and **shrub**, as represented, respectively, by *Sphagnum papillosum*, *Eriophorum vaginatum*, and *Calluna vulgaris*. These PFTs were chosen because a distinction is often made when looking at plant litter breakdown and peat formation between mosses, sedges and shrubs (e.g. **Frolking *et al*. 2001, 2010**; **Moore *et al*., 2007**). Two sulphur amendments were also considered in Experiment 2 (no sulphate addition (deionised water application) versus a single application equivalent to 100 kg S ha^{-1} yr^{-1}). **The single application was made in week 17 of the nine-month experimental run, which was at the transition from simulated July to simulated August conditions**. A single water-table regime was employed in Experiment 2 to avoid proliferation of treatments (see below).

Water-tables in the peat samples were allocated either a constant or variable depth below the surface. In Experiment 1 water tables were held at a depth of 2 cm below ground level (bgl) in the 'constant water-table' treatment. In the 'variable water-table' treatment, water tables varied from surface inundation to a maximum depth of 10 cm bgl. In Experiment 2 a variable water-table regime was used for all peat samples, with the highest water-table position being 3 cm bgl and the lowest 13 cm bgl. These depths were based on judgement and data from other peatland projects (at Leeds and CEH) and reflect variability encountered in the field. Water-table levels were maintained manually using the overflow tube and water collected from a reservoir near the field site.

Table 2.2. *Treatments used in Experiment 1*.

	Restoration method/outcome			
Water level (WL) and climate (C) scenario	Peat dam with pool (no infill)	Peat dam with *Sphagnum* mat	Dammed with heather bale infill	Re-profiled
WL1 – CL1	3	3	3	3
WL1 – CL2	3	3	3	3
WL2 – CL1	3	3	3	3
Total no. samples:	**9**	**9**	**9**	**9**

Note: WL1 indicates a stable water level, WL2 a fluctuating water level. C1 indicates existing climate, C2 a future possible climate. See text for further details.

Table 2.3. *Treatments used in Experiment 2*.

	Plant functional type		
Sulphur (S) and climate (C) scenario	Moss (*Sphagnum papillosum*)	Sedge (*Eriophorum vaginatum*)	Shrub (*Calluna vulgaris*)
S1 – C1	3	3	3
S2 – C1	3	3	3
S2 – C2	3	3	3
Total no. samples:	**9**	**9**	**9**

Note: S1 indicates no sulphate amendment, and S2 sulphate addition. C1 indicates existing climate, C2 a future possible climate. All samples had a variable water-table regime. See text for further details.

PAR was measured daily above all of the peat samples using a Skye Instruments PAR Quantum Sensor to check that each mesocosm and each treatment received equivalent amounts of incoming radiation. No significant differences were found between treatments. For example, during within-cabinet conditions representing May-time weather (Table 2.1), the treatments had the following means and standard deviations of PAR photon flux density.

Experiment 1: no infill = 286 ± 28.9 μmol m^{-2} s^{-1}; *Sphagnum* mat = 283 ± 25.4 μmol m^{-2} s^{-1}; heather bale = 267 ± 58.2 μmol m^{-2} s^{-1}; re-profiling = 286 ± 52.6 μmol m^{-2} s^{-1} (p = 0.767 [one-way ANOVA]).

Experiment 2: *Sphagnum papillosum* = 279 ± 36.5 μmol m^{-2} s^{-1}; *Eriophorum vaginatum* = 278 ± 27.9 μmol m^{-2} s^{-1}; *Calluna vulgaris* = 278 ± 23.6 μmol m^{-2} s^{-1}) (p = 0.995 [one-way ANOVA]).

We provided the peat samples with artificial rainfall that was matched in chemical composition with rainfall at the field site (Na^+ = 2.01 mg L^{-1}, Mg^{2+} = 0.43 mg L^{-1}, Ca^{2+} = 0.32 mg L^{-1}, K^+ = 0.12 mg L^{-1}, NH_4^+ = 0.25 mg L^{-1}, NO_3^- = 0.58 mg L^{-1}, SO_4^{2-} = 2.01 mg L^{-1}, Cl^- = 3.20 mg L^{-1}; pH adjusted to 5.13). A total of 50-150 mL of artificial precipitation was added to each peat sample per week, the exact amount depending on transpiration from mesocosms containing different plant functional types and also on whether or not the water table was held stable (WL1) or whether its position was being altered (high to low and *vice versa* – WL2).

Respiration from peat mesocosms can increase cabinet CO_2 concentrations to values in excess of 500 ppm, thus rendering the results of incubations unreliable (such high concentrations are not usually seen in the field). Therefore, **ambient CO_2 concentrations were maintained at 380 ppm (± 50 ppm)**, a level found in well-mixed (windy) conditions in the field. The ability to control above-canopy CO_2 concentrations was identified as a major advantage of our experimental design in our original proposal to Defra. Without such CO_2 control, the mesocosms would have experienced unrealistic CO_2 concentrations in the region of 450-700 ppm, with the likely effect of artificial stimulation of CH_4 emissions.

Figure 1.2. *A selection of the peat samples (mesocosms) from Experiment 1. Photograph: Sophie Green.*

2.4 Measurement of diffusive/plant-mediated/steady ebullition gas emissions

Flux chambers were used to estimate 'steady' CH_4, CO_2 and N_2O exchanges between the mesocosms and the atmosphere. 'Steady' refers to the combination of diffusive movement of each gas through the soil and plant tissues and the steady release of bubbles to the peatland surface (see **Green and Baird, in press and in review**). The flux chambers used in this study comprised a foam-sealed acrylic chamber which was placed on to cylindrical collars fitted to the top of the PVC cylinders holding the peat samples/mesocosms. Each chamber was fitted with a fan to circulate within-chamber air, a pressure-equalisation balloon (to ensure chamber air was at the same pressure as air outside the chamber), and ice-packs to prevent within-chamber temperatures rising above ambient. The methods for determining the concentration of each gas during a flux-chamber test are briefly described below, as are the data analysis methods.

2.4.1 Methane (CH_4)

During a flux chamber test, within-chamber CH_4 concentrations were measured 'on-line' (real-time) using a Los Gatos Inc. Fast Methane Analyser (FMA) which uses cavity ring-down laser spectroscopy to measure the concentration of CH_4 – [CH_4] – in gas samples. Chamber gas circulates in a closed loop through inlet and outlet tubes running, respectively, between the FMA and the flux chamber and between the flux chamber and the FMA. Because the FMA gives rapid determinations of flux-chamber [CH_4], flux-chamber tests only needed to be run for *c*. 2-3 minutes to provide enough data (typically more than six data values, and often as many as 12) from which to estimate CH_4 emissions (see below this section). Flux-chamber tests for CH_4 emissions were made **weekly** during each experiment.

The flux-chamber test data were analysed by fitting a regression line to the data and using the slope of the line to estimate fluxes. This is a standard method and is also discussed by **Denmead (2008)** and used by **Green and Baird (in press and in review)**. The slope of the regression line of chamber [CH_4] over time was used for estimating fluxes, provided $r^2 \geq 0.8$ and $p < 0.05$. If CH_4 concentrations did not change by more than 0.003 ppm during a flux chamber test, fluxes were assumed to be zero. In all other cases the data were rejected. In practice, few flux test data were rejected (< 2.8 % across both experiments).The purpose of the flux chamber tests was to estimate steady fluxes. Therefore, any small episodic ebullition fluxes during flux chamber measurements (revealed by step increases in flux chamber [CH_4]) were discounted, and only the steady component of the flux estimated. Episodic ebullition was estimated separately (see section 2.5).

2.4.2 Carbon dioxide (CO_2)

Net ecosystem exchange (NEE) provides a direct measure of the net CO_2 exchange between ecosystems and the atmosphere. NEE represents the balance between soil/plant respiration and photosynthetic uptake and assimilation across both daytime and night-time conditions. Daytime and night-time CO_2 fluxes (NEE is the sum of the two) were measured on a **monthly** basis using the flux chambers. During the flux-chamber tests, CO_2 concentrations were measured using a real-time PP Systems CIRAS2 portable infrared gas analyser (IRGA) fitted to the chamber. The instrument measures rates of change in [CO_2] over a defined period (90 s; linear and non-linear trends are flagged by the instrument automatically), and thereafter, the rates of gas exchange are calculated (see **Denmead, 2008**). We use the convention that **a positive NEE indicates a net release of CO_2 to the atmosphere, while a negative value indicates a net uptake of CO_2 from the atmosphere**. Thus, an increase in NEE would indicate less CO_2 being taken up by the peat samples or a greater rate of net CO_2 loss.

2.4.3 Nitrous oxide (N_2O)

Steady N_2O fluxes were measured on a **monthly** basis using flux chambers fitted to a Gas Filter Correlation N_2O analyser (Teledyne Analytical Instruments, Model GFC-7002E) over a five-minute period. This instrument is connected to the flux chamber in a similar way to the IRGA (see section 2.4.2) and the FMA (section 2.4.1). The five-minute period was sufficient to register changes in N_2O concentration (when fluxes were non-zero) while meeting the tight timing constraints of our analytical programme.

2.5 Measurement of CH_4 emissions due to episodic ebullition

Bubble loss was estimated by weighing the peat samples on a **weekly** basis. The samples had set water-tables, so any differences in weight between dates was due either to bubble build-up (where water displaced by growing bubbles was collected in an overflow device) or bubble loss. By careful screening of the data, we were able to estimate the volume of bubbles lost from peat samples. To estimate a CH_4 flux, it was necessary to estimate the CH_4 concentration in the bubbles, and it was assumed that the CH_4 content of bubbles was in equilibrium with pore-water CH_4 concentrations (see section 2.6 below).

Ebullition monitoring ceased after the simulated August-time meteorological conditions (Table 2.1) because it has been demonstrated in previous controlled-environment studies **(Green and Baird, in review)** that ebullition events are rarely evident under autumn conditions and because ebullition fluxes from the mesocosms were found to be very low (see sections 3.1.1 and 3.1.2).

2.6 Measurement of pore-water chemical composition

2.6.1 Pore-water extraction

In both Experiment 1 and Experiment 2, pore-water was extracted **weekly** from the sampling ports in the side (see section 2.2) of the holder of each mesocosm. Where possible, approximately 60 mL of pore water was extracted from each port under suction. However, the lowermost ports rarely yielded this much because of the low permeability of the peat at this depth, so that there was insufficient sample for analysis. After all the pore-water samples from a mesocosm were taken, the water-table was re-established to its defined level using artificial precipitation (see section 2.3 for chemical composition).

2.6.2 Measuring pore-water [CH_4]

Weekly measurements were made of pore-water [CH_4] using a headspace technique. 1 mL of the pore-water extract was injected into 20-mL, N_2-flushed mini-vials (Chromacol LTD, Welwyn Garden City, Hertfordshire, UK). After shaking for 24 hours, the headspace gas from each vial was analysed for CH_4 content using a Cambridge Ai gas chromatograph (GC) system fitted with a flame ionisation detector (FID). In the system, gases are separated on a stainless steel column packed with Porapak (Q 80/100) at 30°C with zero-grade N_2 as the carrier gas. Headspace concentrations of CH_4 were calculated from peak areas calibrated against known standards (Scientific and Technical Gases, Staffordshire, UK). Standard analytical grade reference span gases were analysed at regular intervals to check for drift. The pore-water [CH_4] data were used as part of our estimate of episodic ebullition flux (see section 2.5).

2.6.3 Cations, anions, acetate, and DOC

To provide contextual data and to help compare treatments, we undertook a **monthly** analysis of dissolved organic carbon (DOC), cation content (Na^+, K^+, Ca^{2+}, Mg^{2+} and NH_4^+), anion content (Cl^-, NO_3^-, PO_4^{3-}, Fl^- and SO_4^{2-}) and acetate content of pore water at a single depth (15 cm) in each mesocosm. Pore-water samples were filtered using syringe filter tips 0.45μm (Chromacol LTD, Welwyn Garden City, Hertfordshire, UK) (see section 2.2). The pore-water samples were analysed using a Shimadzu TOC-V CSN with ASI-V Autosampler (DOC) and ion chromatography, a Dionex ICS2500 and DX100 with Chromeleon software, and an AS50 auto-sampler (cations, anions and acetate). Solute concentrations were calculated from peak areas calibrated against known standards. Standards were also analysed at regular intervals during sample runs to check for drift.

2.7 Estimating global warming potential (GWP)

The radiative forcing effect of CH_4 and other GHGs was calculated using the Intergovernmental Panel on Climate Change (IPCC) GWP approach as outlined in **Baird *et al*. (2009)** (see also **Soloman *et al*., 2007**; **Forster *et al*., 2007**). Using this approach, GWP here is described in terms of **carbon dioxide equivalent emissions (CO_2-e)**.

2.8 Statistical analysis

For the majority of statistical tests, the **significance level was set at $p \leq 0.05$** (episodic ebullition being the exception – see section 3.1.1 for further explanation). Statistical analyses were performed using SPSS version 16.0.0 (2007), and graphs were produced using Statistica version 9. Details of each test are given below.

Experiment 1.
Hypothesis 1: Two-way ANOVA (Analysis of Variance) with restoration or grip blocking method and climate as factors (data from the mesocosms comprising the treatments identified in rows 1 and 2 of Table 2.2).
Hypotheses 2/3: Two-way ANOVA with restoration method and water-table regime as factors (rows 1 and 3 of Table 2.2).
Hypothesis 4: We were unable to test this hypothesis formally because we found that N_2O levels were below detection limits (see section 3.1.2). However, the fact that N_2O levels were so low suggests that **the hypothesis may be tentatively rejected**; even if N_2O levels had increased, such increases were below detection and not of any consequence in terms of GWP.
Hypothesis 5: Two-way ANOVA with restoration method and climate (rows 1 and 2 of Table 2.2 – this ANOVA was the same as that used to test Hypothesis 1).

Experiment 2.
Hypothesis 6: Two-way ANOVA with PFT and climate as factors (**pre sulphate treatment data** from the mesocosms comprising the treatments identified in all the rows in Table 2.3).
Hypothesis 7: Two-way ANOVA with PFT and sulphate application as factors (**post sulphate treatment data** – rows 1 and 2 in Table 2.3).
Hypothesis 8: Two-way ANOVA with PFT and climate as factors (**post sulphate treatment data** – rows 2 and 3 in Table 2.3).
Hypothesis 9: Two-way ANOVA with PFT and climate as factors (**pre sulphate treatment data** – all rows in Table 2.3 – this ANOVA was the same as that used for Hypothesis 6).

Where our significance criterion was met, a post-hoc test (SNK) was employed to identify which individual treatments contributed to any significant differences observed within response variables. As well as the response variable directly related to each hypothesis, we ran additional ANOVA tests using the following as response variables: GWP, NEE, pore-water [CH_4], pore-water [cations], pore-water [anions], pore-water [acetate], and pore-water [DOC]. Prior to the ANOVA tests, all data were checked for normality and equality of variance. If the assumptions of ANOVA were not met, the data were $\log_{10}$-transformed (with a constant applied for negative values where necessary). The response variables were the averages for each core for the duration of the experiment, except with Hypotheses 6-9 where we used averages for either the pre- or post- sulphur treatment period.

3. Results

3.1 Experiment 1

3.1.1 Effect of restoration method (infill) on blocked/dammed grip CH_4 emissions

Hypothesis 1: CH_4 emissions will differ according to the grip block method.
Table 3.1 shows the mean steady CH_4 flux expressed in daily and yearly rates (**mg** CH_4 m^{-2} $\mathbf{d^{-1}}$, **g** CH_4 m^{-2} $\mathbf{y^{-1}}$), mean episodic ebullition flux (mg CH_4 m^{-2} d^{-1}), mean NEE (**mg** CO_2 m^{-2} $\mathbf{d^{-1}}$, **g** CO_2 m^{-2} $\mathbf{y^{-1}}$), and GWP (g CO_2-e m^{-2} y^{-1}) for the four restoration outcomes under the two climate scenarios (CL1 and CL2). It was found that the re-profiling (37.6 ± 6.2 mg CH_4 m^{-2} d^{-1}), heather bale (22.7 ± 6.23 mg CH_4 m^{-2} d^{-1}) and *Sphagnum* mat (36.4 ± 6.2 mg CH_4 m^{-2} d^{-1}) infill mesocosms had significantly higher mean steady CH_4 fluxes than the no-infill (i.e., pooled) samples (-0.95 ±6.23 mg CH_4 m^{-2} d^{-1}) (F = 28.59; p < 0.001). **Therefore, Hypothesis 1 may be accepted**.

It should be noted that many fluxes given in the text represent values aggregated at a higher level than is the case in the tables. For example, the figure given in the previous paragraph for *Sphagnum* mat infill mesocosms – 36.4 ± 6.2 mg CH_4 m^{-2} d^{-1} – represents the average of the separate values given for *Sphagnum* mats under CL1 and CL2 in Table 3.1 (41.7 and 31.0 mg CH_4 m^{-2} d^{-1}). In addition, we present

standard errors as pooled standard errors. In experiments with small numbers of replicates such as the mesocosm study it is common to pool the variance (and therefore the standard error) in this way (this pooling happens within ANOVA, for example).

Mesocosms representing pools showed no net CH_4 loss or even a slight uptake (i.e., negative fluxes associated with uptake and oxidation of atmospheric CH_4) in contrast to the CH_4 losses to the atmosphere observed from the other three restoration outcomes. The mesocosms representing re-profiling showed large changes in plant composition over the experimental period (Figure 3.1), from essentially bare peat to a full plant cover, which affected their emission rates into autumn and winter (Figure 3.2).

NEE was also significantly different between restoration method ($F = 24.9$; $p < 0.0001$), with the restoration method statistically separating into three distinct sub-sets: *Sphagnum* mat (383 ± 447 mg CO_2 m^{-2} d^{-1}) = no infill (804 ± 447 mg CO_2 m^{-2} d^{-1}) < re-profiling (2128 ± 447 mg CO_2 m^{-2} d^{-1}) < heather bale (5311 ± 447 mg CO_2 m^{-2} d^{-1}). GWP was also significantly different between restoration methods, with no-infill (285 ± 160 g CO_2-e m^{-2} y^{-1}) = *Sphagnum* mat (471 ± 160 g CO_2-e m^{-2} y^{-1}) < re-profiling (1120 ± 160 g CO_2-e m^{-2} y^{-1}) < heather bale (2146 ± 160 g CO_2-e m^{-2} y^{-1}) ($F = 30.5$, $p < 0.0001$). It is important to note that all GWP values are positive; therefore, **all of the restoration outcomes result in the peatland having a net radiative or warming effect**. However, it is also important to note that this finding is based on nine simulated months and **does not compare the restoration methods with a no-restoration treatment**.

The normality and variance of the ebullition flux data did not meet the requirements for the application of two-way ANOVA. However, the validity of the non-parametric alternative is still unclear (**Dytham, 2003**). With this in mind, a two-way ANOVA was used, but with a more stringent significance level applied ($p \leq 0.01$). Twenty-four episodic ebullition events were identified in Experiment 1 under spring and summer meteorological conditions (Table 2.1). The maximum episodic ebullition CH_4 flux (average for a week) occurred under May-time conditions from a *Sphagnum* mat core (4.19 mg CH_4 m^{-2} d^{-1}). *Sphagnum* mats (0.21 ± 0.03 mg CH_4 m^{-2} d^{-1}) had a significantly-higher ebullition CH_4 flux than no-infill (0.0000 (4 decimal places) ± 0.03 mg CH_4 m^{-2} d^{-1}), heather bale (0.0020 (4 d.p.) ± 0.03 mg CH_4 m^{-2} d^{-1}) and re-profiling (0.0005 (4 d.p.) ± 0.03 mg CH_4 m^{-2} d^{-1}) ($F = 11.6$, $p < 0.0001$). Episodic ebullition CH_4 flux contributed less than 1% to the total CH_4 efflux for all restoration outcomes. Episodic ebullition was excluded from the GWP calculations because of these low totals.

Table 3.2 shows the mean pore-water [CH_4] for the four restoration outcomes under CL1 and CL2 for 5- and 15-cm depth. It was found that at a depth of 5 cm all restoration outcomes were significantly different from each other: no-infill (0.03 ± 0.11 mg L^{-1}) < re-profiling (0.11 ± 0.11 mg L^{-1}) < heather bale (0.26 ± 0.11 mg L^{-1}) < *Sphagnum* mat (2.27 ± 0.11 mg L^{-1}) ($F = 69.6$, $p < 0.0001$). The 15-cm data showed a similar pattern ($F = 46.9$, $p < 0.0001$): no infill (0.06 ± 0.46 mg L^{-1}) < re-profiling (0.61 ± 0.46 mg L^{-1}) = heather bale (0.24 ± 0.46 mg L^{-1}) < *Sphagnum* mat (5.14 ± 0.46 mg L^{-1}). In addition, pore-water [CH_4] significantly increased with depth ($F = 12.6$, $p = 0.003$).

Table 3.3 shows the mean concentrations of base cations, anions, acetate and dissolved organic carbon (DOC) at 15 cm depth for the four restoration outcomes under CL1 and CL2. It was found that K^+, Mg^{2+}, Cl^-, NO_3^- and DOC significantly differed between restoration outcomes as follows:
K^+: $F = 6.45$, $p = 0.007$: (no-infill = *Sphagnum* mat = re-profiling) < (re-profiling = heather bale)
Mg^{2+}: $F = 4.90$, $p = 0.018$: (*Sphagnum* mat = no-infill = re-profiling) < (re-profiling = heather bale)
Cl^-: $F = 5.93$, $p = 0.009$: no-infill < *Sphagnum* mat = re-profiling = heather bale
NO_3^-: $F = 1298$, $p < 0.0001$: re-profiling < no infill = *Sphagnum* mat = heather bale
DOC: $F = 7.602$, $p = 0.003$: (no-infill = *Sphagnum* mat = re-profiling) < (re-profiling = heather bale).
All other pore-water response variables did not exhibit any statistically-significant differences between restoration outcomes (Table 3.3).

Table 3.1. *Steady mean CH_4 flux (mg CH_4 m^{-2} d^{-1}, g CH_4 m^{-2} y^{-1}), mean ebullition CH_4 flux (mg CH_4 m^{-2} d^{-1}) (spring and summer data only), NEE (mg CO_2 m^{-2} d^{-1}, g CO_2 m^{-2} y^{-1}), and global warming potential (g CO_2-e m^{-2} y^{-1}) for the four restoration outcomes under CL1 and CL2 (*n *= 24). Episodic ebullition was not included in the GWP calculations. Positive fluxes indicate emissions, and negative indicate uptake. Parentheses show standard error.*

Climate	Restoration outcome	Steady CH_4 flux (mg CH_4 m^{-2} d^{-1})	Steady CH_4 flux (g CH_4 m^{-2} y^{-1})	Episodic ebullition flux (mg CH_4 m^{-2} d^{-1})	NEE (mg CO_2 m^{-2} d^{-1})	NEE (g CO_2 m^{-2} y^{-1})	GWP (g CO_2 m^{-2} y^{-1})
CL1	No-infill	-0.64 (±8.82)	**-0.23 (±3.22)**	0.00 (± 0.04)	800 (±632)	**292 (±231)**	286 (±226)
	Sphagnum mat	41.7 (±8.82)	**15.2 (±3.22)**	0.22 (± 0.04)	780 (±632)	**285 (±231)**	666 (±226)
	Heather bale	19.8 (±8.82)	**7.22 (±3.22)**	0.003 (± 0.04)	4676 (±632)	**1707 (±231)**	1887 (±226)
	Re-profiling	35.0 (±8.82)	**12.8 (±3.22)**	0.001 (± 0.04)	2453 (±632)	**895 (±231)**	1215 (±226)
CL2	No-infill	-1.26 (±8.82)	**-0.46 (±3.22)**	0.00 (± 0.04)	807 (±632)	**295 (±231)**	283 (±226)
	Sphagnum mat	31.0 (±8.82)	**11.3 (±3.22)**	0.2 (± 0.04)	-15.0 (±632)	**-5.47 (±231)**	277 (±226)
	Heather bale	25.7 (±8.82)	**9.37 (±3.22)**	0.001 (± 0.04)	5946 (±632)	**2170 (±231)**	2404 (±226)
	Re-profiling	40.2 (±8.82)	**14.7 (±3.22)**	0.00 (± 0.04)	1804 (±632)	**658 (±231)**	1026 (±226)

Note: the data in the bolded columns are effectively the same as those in the columns to their immediate left. The mean daily fluxes represent means for the duration of the experiment (nine months). For the bolded columns, these means have simply been scaled to a year. **Therefore, the fluxes expressed on a yearly basis are probably too high for CH_4 and too low for NEE because winter and early spring (January, February, and March) values are not included.**

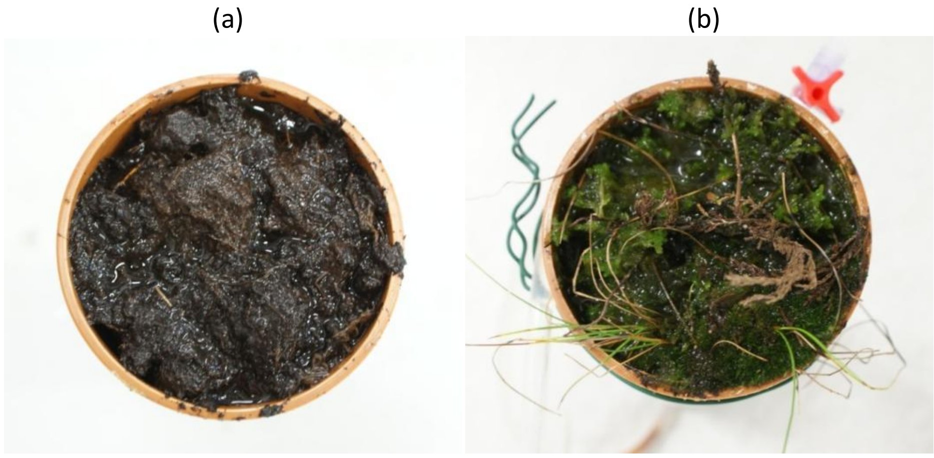

Figure 3.1. *A re-profiling core, illustrating the change in vegetation cover over time. Photograph (a) 12th July 2010 (week 1 of experiment) and (b) 22nd April 2011 (week 39). Photographs: Sophie Green.*

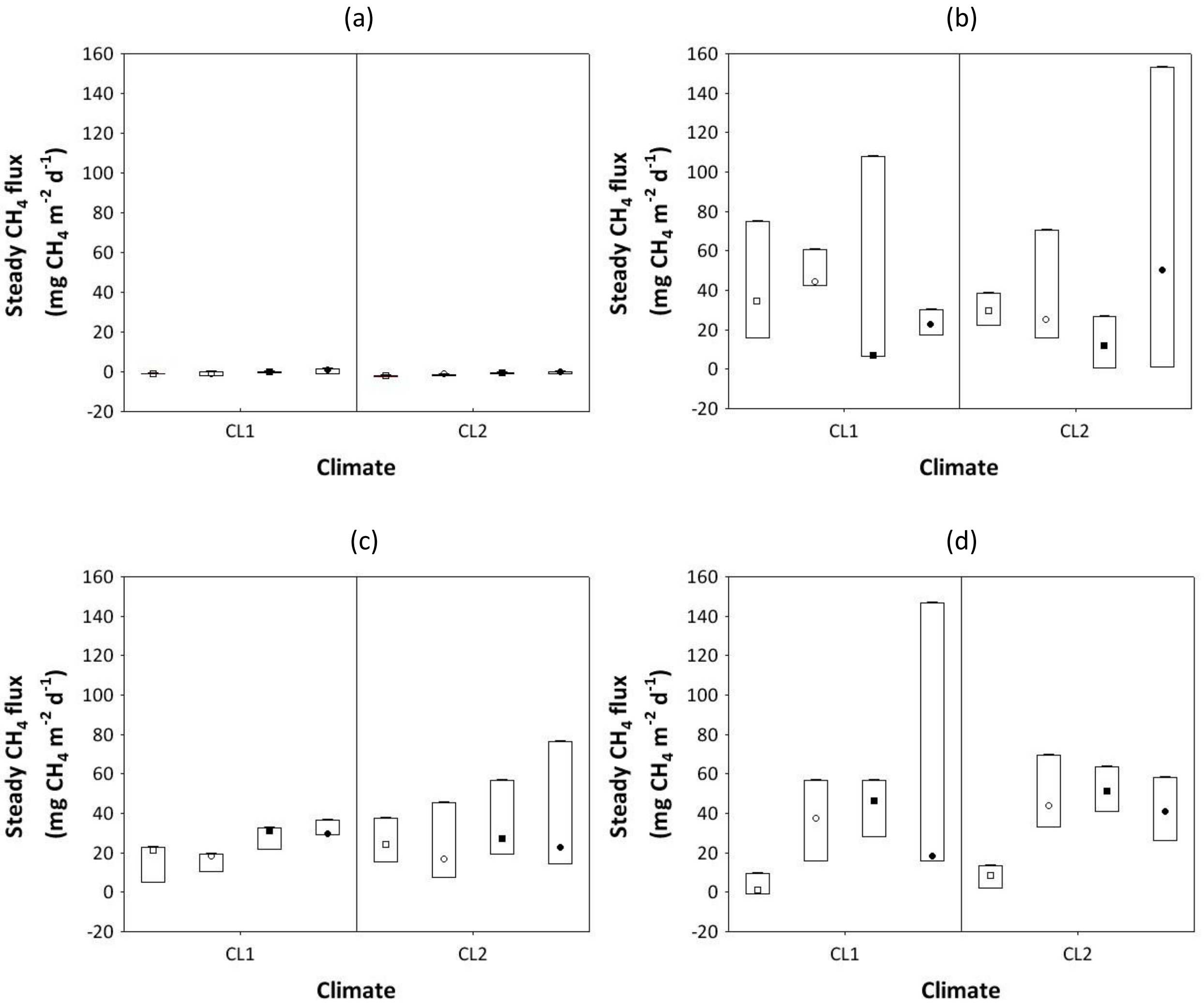

Figure 3.2. *Box plots of seasonal steady CH_4 fluxes disaggregated by restoration outcome: (a) no infill (i.e. pooled), (b)* Sphagnum *mat, (c) heather bale, and (d) re-profiling. Median is represented by the symbol (open square = spring (April, May), open circle = summer (June, July, August), filled square = autumn (September, October, November), filled circle = winter (December)), with the box representing the inter-quartile range and the whiskers indicating the full range.*

Table 3.2. *Mean pore-water [CH_4] at 5- and 15- cm depth for the four restoration outcomes under CL1 and CL2 (*n *= 24). Parentheses show standard error.*

Climate	**Restoration outcome**	[CH_4] 5 cm (mg L^{-1})	[CH_4] 15 cm (mg L^{-1})
CL1	No-infill	0.03 (± 0.15)	0.07 (± 0.66)
	Sphagnum mat	1.94 (± 0.15)	4.36 (± 0.66)
	Heather bale	0.15 (± 0.15)	0.21 (± 0.66)
	Re-profiling	0.12 (± 0.15)	0.07 (± 0.66)
CL2	No-infill	0.03 (± 0.15)	0.04 (± 0.66)
	Sphagnum mat	2.61 (± 0.15)	5.91 (± 0.66)
	Heather bale	0.37 (± 0.15)	0.27 (± 0.66)
	Re-profiling	0.11 (± 0.15)	1.16 (± 0.66)

Table 3.3. *Mean concentrations (all mg L^{-1}) of base cations, anions, acetate and DOC at 15-cm depth for the four restoration outcomes under CL1 and CL2 (*n *= 24). Parentheses show standard error.*

Climate	Restoration outcome	[Na^+]	[NH_4^+]	[K^+]	[Mg^{2+}]	[Ca^{2+}]	[Cl^-]	[PO_4^{3-}]	[NO_3^-]	[SO_4^{2-}]	[Acetate]	[DOC]
CL1	No-infill	14.8 (±0.65)	1.43 (±0.52)	3.28 (±2.26)	1.29 (±0.62)	2.26 (±0.57)	10.8 (±0.85)	1.12 (±0.95)	0.66 (±0.24)	4.02 (±0.80)	8.89 (±4.86)	45.7 (±21.4)
	Sphagnum mat	12.4 (±0.65)	1.27 (±0.52)	2.23 (±2.26)	1.08 (±0.62)	2.61 (±0.57)	11.0 (±0.85)	1.67 (±0.95)	0.57 (±0.24)	3.70 (±0.80)	3.09 (±4.86)	18.9 (±21.4)
	Heather bale	12.9 (±0.65)	2.66 ±0.52)	11.0 (±2.26)	3.07 (±0.62)	3.66 (±0.57)	14.76 (±0.85)	5.16 (±0.95)	1.43 (±0.24)	3.60 (±0.80)	16.39 (±4.86)	95.9 (±21.4)
	Re-profiling	14.9 (±0.80)	1.49 (±0.64)	11.3 (±2.77)	2.98 (±0.76)	4.06 (±0.69)	14.54 (±1.04)	2.71 (±1.17)	1.50 (±0.29)	4.58 (±0.97)	8.67 (±5.95)	110 (±26.2)
CL2	No-infill	11.5 (±0.65)	1.57 (±0.52)	1.79 (±2.26)	1.24 (±0.62)	2.74 (±0.57)	9.19 (±0.85)	2.44 (±0.95)	0.57 (±0.24)	3.85 (±0.80)	5.62 (±4.86)	9.72 (±21.4)
	Sphagnum mat	12.2 (±0.65)	4.07 (±0.52)	5.16 (±2.26)	1.48 (±0.62)	2.72 (±0.57)	12.8 (±0.85)	6.25 (±0.95)	0.88 (±0.24)	2.58 (±0.80)	3.67 (±4.86)	62.4 (±21.4)
	Heather bale	12.1 (±0.65)	0.93 (±0.52)	8.52 (±2.26)	2.95 (±0.62)	4.09 (±0.57)	11.9 (±0.85)	0.99 (±0.95)	0.80 ±0.24)	3.46 (±0.80)	12.4 (±4.86)	137 (±21.4)
	Re-profiling	10.3 (±1.13)	0.37 (±0.90)	0.47 (±3.92)	0.78 (±1.08)	1.12 (±0.98)	9.09 (±1.47)	0.00 (±1.65)	0.00 (±0.41)	5.48 (±1.38)	0.00 (±8.41)	57.5 (±25.3)

Note: the concentrations in the table are for the compounds, and not elements within the compounds. Thus, for example, [NO_3^-] has units of mg NO_3^- L^{-1} and **not** mg NO_3^--N L^{-1}.

3.1.2 Effect of water level on GHG emissions

Hypothesis 2: A high and static water table promotes CH_4 emissions.
Hypothesis 3: A fluctuating water table reduces CH_4 emissions.
Hypotheses 2 and 3 can be considered together and were tested with a single two-way ANOVA. Table 3.4 shows the mean steady CH_4 flux expressed in daily and yearly rates (**mg** CH_4 m^{-2} $\mathbf{d^{-1}}$, **g** CH_4 m^{-2} $\mathbf{y^{-1}}$), mean episodic ebullition flux (mg CH_4 m^{-2} d^{-1}), mean NEE (**mg** CO_2 m^{-2} $\mathbf{d^{-1}}$, **g** CO_2 m^{-2} $\mathbf{y^{-1}}$), and GWP (g CO_2-e m^{-2} y^{-1}) for the four restoration outcomes under the two water-table regimes (WL1 and WL2). There was no significant difference between WL1 (constant water table) (24.0 ± 5.03 mg CH_4 m^{-2} d^{-1}) and WL2 (variable water table) (31.1 ± 5.03 mg CH_4 m^{-2} d^{-1}) ($F = 0.14$, $p = 0.71$). **Therefore, Hypotheses 2 and 3 may be rejected.** It was also found that *Sphagnum* mat (64.5 ± 7.11 mg CH_4 m^{-2} d^{-1}) mesocosms had significantly higher CH_4 fluxes than the re-profiling (23.7 ± 7.11 mg CH_4 m^{-2} d^{-1}), heather bale (22.6 ± 7.11 mg CH_4 m^{-2} d^{-1}), and no-infill (i.e. pooled) samples (-0.62 ± 7.11 mg CH_4 m^{-2} d^{-1}) ($F = 37.0$; $p < 0.0001$).

NEE was significantly different between restoration method ($F = 45.6$; $p < 0.0001$), with three distinct sub-sets: *Sphagnum* mat (499 ± 256 mg CO_2 m^{-2} d^{-1}) = no infill (694 ± 256 mg CO_2 m^{-2} d^{-1}) < re-profiling (2162 ± 256 mg CO_2 m^{-2} d^{-1}) < heather bale (4240 ± 256 mg CO_2 m^{-2} d^{-1}). **NEE was significantly influenced by water-table regime** ($F = 4.74$, $p = 0.045$), **being higher under a constant water table** (2177 ± 181 mg CO_2 m^{-2} d^{-1}) than a variable water-table (1620 ± 181 mg CO_2 m^{-2} d^{-1}). Like steady CH_4 flux and NEE, **GWP was significantly different between restoration outcomes, but was not influenced by water-table regime** (restoration method: $F = 31.0$, $p < 0.0001$; water-table regime: $F = 1.51$, $p = 0.24$).

Episodic ebullition fluxes were significantly different between restoration method, with *Sphagnum* mat (0.11 ± 0.02 mg CH_4 m^{-2} d^{-1}) being higher than no-infill (0.0000 (4 decimal places) ± 0.02 mg CH_4 m^{-2} d^{-1}), heather bale (0.0014 (4 d.p.) ± 0.02 mg CH_4 m^{-2} d^{-1}) and re-profiling (0.0005 ± 0.02 mg CH_4 m^{-2} d^{-1}) ($F = 5.3$, $p = 0.01$). No ebullition events were evident in mesocosms under a variable water table (WL2). Using a significance criterion of $p \leq 0.01$ (see section 3.1.1) there was no significant difference between water-table regime ($F = 5.68$, $p = 0.03$).

Table 3.5 shows the mean pore-water [CH_4] for the four restoration methods under WL1 and WL2 for 5- and 15-cm depths. It was found that at a depth of 5 cm all restoration methods were significantly different from each other: no-infill (0.03 ± 0.12 mg L^{-1}) < re-profiling (0.09 ± 0.12 mg L^{-1}) < heather bale (0.17 ± 0.12 mg L^{-1}) < *Sphagnum* mat (1.45 ± 0.12 mg L^{-1}) ($F = 64.2$, $p < 0.0001$). At 15 cm a similar result was obtained ($F = 38.5$, $p < 0.0001$): no infill (0.06 ± 0.59 mg L^{-1}) = re-profiling (0.06 ± 0.59 mg L^{-1}) < heather bale (0.23 ± 0.59 mg L^{-1}) < *Sphagnum* mat (4.23 ± 0.59 mg L^{-1}). In addition, pore-water [CH_4] significantly increased with depth ($F = 12.6$, $p = 0.003$). The water-table regime had no significant effect on pore-water [CH_4] at either depth (5 cm: F = 0.76, $p = 0.399$; 15 cm: F = 0.67, $p = 0.427$).

Table 3.6 shows the mean concentrations of base cations, anions, acetate and DOC at 15-cm depth for the four restoration outcomes under WL1 and WL2. It was found that SO_4^{2-} and DOC significantly differed between restoration outcomes as follows:
SO_4^{2-}: $F = 6.81$, $p = 0.005$: *Sphagnum* mat < heather bale = no-infill < re-profiling.
DOC: $F = 8.106$, $p = 0.003$: (no infill = *Sphagnum* mat) < (*Sphagnum* mat = heather bale = re-profiling).

The concentration of sulphate was significantly higher under a constant water table (WL1) ($F = 5.073$, $p = 0.042$). There were no statistically-significant interaction effects between restoration outcome and water-table regime for any of the pore-water response variables.

It should be noted that the number of pore-water samples collected from cores representing re-profiling under WL2 were low because very few ports in these mesocosms yielded enough water for analysis (presumably because of the low permeability of the re-profile infill). In consequence, a mean value is not given in Table 3.6 (denoted by .a), and the results relating to re-profiling pore-water chemistry should be considered with caution.

Table 3.4. *Steady mean CH_4 flux (mg CH_4 m^{-2} d^{-1}, g CH_4 m^{-2} y^{-1}), mean ebullition CH_4 flux (mg CH_4 m^{-2} d^{-1}) (spring and summer data only), NEE (mg CO_2 m^{-2} d^{-1}, g CO_2 m^{-2} y^{-1}), and global warming potential (g CO_2-e m^{-2} y^{-1}) for the four restoration outcomes under WL1 and WL2 (n = 24). Episodic ebullition is not included in the GWP calculations. Positive fluxes indicate emissions, and negative indicate uptake. Parentheses show standard error.*

Water-table regime	**Restoration outcome**	Steady CH_4 flux (mg CH_4 m^{-2} d^{-1})	Steady CH_4 flux (g CH_4 m^{-2} y^{-1})	Episodic ebullition flux (mg CH_4 m^{-2} d^{-1})	NEE (mg CO_2 m^{-2} d^{-1})	NEE (g CO_2 m^{-2} y^{-1})	GWP (g CO_2 m^{-2} y^{-1})
WL1	No-infill	-0.64 (±10.1)	**-0.23 (±3.67)**	0.00 (±0.03)	800 (±362)	**292 (±132)**	286 (±159)
	Sphagnum mat	41.8 (±10.1)	**15.2 (±3.67)**	0.22 (±0.03)	780 (±362)	**285 (±132)**	666 (±159)
	Heather bale	19.8 (±10.1)	**7.22 (±3.67)**	0.003 (±0.03)	4676 (±362)	**1707 (±132)**	1887 (±159)
	Re-profiling	35.0 (±10.1)	**12.8 (±3.67)**	0.001 (±0.03)	2453 (±362)	**895 (±132)**	1215 (±159)
WL2	No-infill	-0.59 (±10.1)	**-0.22 (±3.67)**	0.00 (±0.03)	587 (±362)	**214 (±132)**	209 (±159)
	Sphagnum mat	87.4 (±10.1)	**31.9 (±3.67)**	0.00 (±0.03)	217 (±362)	**79.2 (±132)**	877 (±159)
	Heather bale	25.4 (±10.1)	**9.29 (±3.67)**	0.00 (±0.03)	3805 (±362)	**1389 (±132)**	1621 (±159)
	Re-profiling	12.3 (±10.1)	**4.50 (±3.67)**	0.00 (±0.03)	1871 (±362)	**683 (±132)**	796 (±159)

Note: the data in the bolded columns are effectively the same as those in the columns to their immediate left. The mean daily fluxes represent means for the duration of the experiment (nine months). For the bolded columns, these means have simply been scaled to a year. Therefore, the fluxes expressed on a yearly basis are probably too high for CH_4 and too low for NEE because winter and early spring (January, February, and March) values are not included.

Table 3.5. *Mean pore-water [CH_4] at 5- and 15- cm depth for the four restoration outcomes under WL1 and WL2 (*n *= 24). Parentheses show standard error.*

Water-table regime	**Restoration outcome**	[CH_4] 5 cm (mg L^{-1})	[CH_4] 15 cm (mg L^{-1})
WL1	No-infill	0.03 (± 0.15)	0.07 (± 0.83)
	Sphagnum mat	1.94 (± 0.15)	4.36 (± 0.83)
	Heather bale	0.15 (± 0.15)	0.21 (± 0.83)
	Re-profiling	0.12 (± 0.15)	0.07 (± 0.83)
WL2	No-infill	0.03 (± 0.15)	0.05 (± 0.83)
	Sphagnum mat	1.03 (± 0.15)	4.10 (± 0.83)
	Heather bale	0.19 (± 0.15)	0.25 (± 0.83)
	Re-profiling	0.06 (± 0.26)	0.04 (± 1.44)

Table 3.6. *Mean concentrations (in mg L^{-1}) of base cations, anions, acetate and DOC at 15-cm depth for the four restoration outcomes under WL1 and WL2 (*n *= 24). Parentheses show standard error.*

Water-table regime	**Restoration outcome**	[Na^+]	[NH_4^+]	[K^+]	[Mg^{2+}]	[Ca^{2+}]	[Cl^-]	[PO_4^{3-}]	[NO_3^-]	[SO_4^{2-}]	[Acetate]	[DOC]
WL1	No-infill	16.3 (±1.58)	1.28 (±0.69)	2.59 (±3.26)	1.28 (±0.89)	2.55 (±0.91)	10.5 (±1.22)	1.74 (±1.39)	0.45 (±0.28)	4.21 (±0.48)	11.9 (±6.55)	26.0 (±29.1)
	Sphagnum mat	12.8 (±1.58)	2.76 (±0.69)	2.60 (±3.26)	0.97 (±0.89)	2.61 (±0.91)	11.2 (±1.22)	3.46 (±1.39)	0.68 (±0.28)	2.64 (±0.48)	1.55 (±6.55)	41.7 (±29.1)
	Heather bale	12.9 (±1.58)	2.00 (±0.69)	11.18 (±3.26)	3.66 (±0.89)	4.51 (±0.91)	13.0 (±1.22)	4.10 (±1.39)	1.42 (±0.28)	4.58 (±0.48)	20.1 (±6.55)	105 (±29.1)
	Re-profiling	13.6 (±1.93)	0.97 (±0.85)	9.53 (±3.99)	3.59 (±1.09)	3.97 (±1.12)	12.2 (±1.49)	4.00 (±1.70)	0.41 (±0.35)	5.90 (±0.59)	20.4 (±8.02)	126 (±35.6)
WL2	No-infill	11.4 (±1.58)	0.68 (±0.69)	0.83 (±3.26)	1.05 (±0.89)	2.86 (±0.91)	9.10 (±1.22)	0.60 (±1.39)	1.01 (±0.28)	3.60 (±0.48)	2.21 (±6.55)	9.71 (±29.1)
	Sphagnum mat	10.8 ±1.58)	2.31 (±0.69)	3.26 (±3.26)	1.19 (±0.89)	2.27 (±0.91)	12.1 (±1.22)	3.23 (±1.39)	0.71 (±0.28)	2.13 (±0.48)	1.80 (±6.55)	36.2 (±29.1)
	Heather bale	14.2 (±1.58)	3.18 (±0.69)	11.57 (±3.26)	3.29 (±0.89)	5.66 (±0.91)	14.0 (±1.22)	1.53 (±1.39)	0.89 (±0.28)	2.78 (±0.48)	6.63 (±6.55)	111 (±29.1)
	Re-profiling	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a	.a

Hypothesis 4: A fluctuating water-table is likely to increase N_2O emissions.
Atmospheric N_2O concentrations were below the levels of detection. Therefore, they could not be included in the GWP calculations and statistical analysis.

3.1.3 Effect of climate on emissions

Hypothesis 5: A warmer climate will lead to higher rates of CH_4 emission.
It was found that **there was no significant difference in mean steady CH_4 flux, NEE, GWP and episodic ebullition flux between CL1 and CL2** (steady CH_4 flux: $F = 0.009$, $p = 0.93$; NEE: $F = 1.99$, $p = 0.18$; GWP: $F = 1.37$, $p = 0.89$; episodic ebullition flux: $F = 0.009$, $p = 0.92$) (Table 3.1). **Therefore, Hypothesis 5 may be rejected**. Pore-water [CH_4] did not significantly differ between CL1 and CL2 (5 cm: $F = 1.68$, $p = 0.21$; 15 cm: $F = 3.41$, $p = 0.08$). Concentrations of Na^+, K^+, Mg^{2+}, Cl^-, and NO_3^- at 15-cm depth were all significantly lower under CL2 (Na^+: $F = 16.8$, $p = 0.001$; K^+: $F = 7.02$, $p = 0.02$; Cl^-: $F = 10.32$, $p = 0.007$; NO_3^-: $F = 2090$, $p <$ 0.0001).

3.2 Experiment 2

3.2.1 Effect of vegetation on CH_4 emissions from inter-grip areas

Hypothesis 6: Different functional plant types will be associated with different fluxes of CH_4.
Table 3.7 shows the mean steady CH_4 flux expressed in daily and yearly rates (**mg** CH_4 m^{-2} $\mathbf{d^{-1}}$, **g** CH_4 m^{-2} $\mathbf{y^{-1}}$), mean NEE (**mg** CO_2 m^{-2} $\mathbf{d^{-1}}$, **g** CO_2 m^{-2} $\mathbf{y^{-1}}$), and GWP (g CO_2-e m^{-2} y^{-1}) for the three plant functional types under the two climate scenarios (CL1 and CL2) (April to July meteorological conditions – all mesocosms). No ebullition events were recorded under the variable water-table regime in Experiment 2. Therefore, episodic ebullition could not be analysed as a response variable.

It was found that the *S. papillosum* (Papillose Bog-moss) mesocosms (68.1 ± 20.2 mg CH_4 m^{-2} d^{-1}) had significantly lower CH_4 fluxes than the *C. vulgaris* (Common Heather) (206 ± 20.2 mg CH_4 m^{-2} d^{-1}) and *E. vaginatum* (Hare's Tail Cotton Grass) (250 ± 20.2 mg CH_4 m^{-2} d^{-1}) samples ($F = 25.3$, $p < 0.0001$). **Therefore, Hypothesis 6 may be accepted**. Figure 3.3 shows the steady CH_4 fluxes from the three plant functional types by season for S1 cores only (no sulphate applied). There were significant differences within each plant functional type with respect to season. *S. papillosum* had significantly lower CH_4 emissions during spring (April, May) than during summer (June, July, August), winter (December) and autumn (September, October, November) ($F = 4.14$, $p = 0.048$). In comparison *E. vaginatum* had lower emission under winter meteorological conditions compared to summer, spring and autumn ($F = 4.27$, $p = 0.045$). *C. vulgaris* had higher emissions under summer and autumn conditions than winter and spring conditions (F = 7.01, p = 0.01).

NEE was significantly different between plant functional types ($F = 16.3$; $p < 0.0001$), with PFT separating into two sub-sets: *E. vaginatum* (708 ± 690 mg CO_2 m^{-2} d^{-1}) = *S. papillosum* (1474 ± 690 mg CO_2 m^{-2} d^{-1}) < *C. vulgaris* (5521 ± 690 mg CO_2 m^{-2} d^{-1}). **GWP was also significantly different between PFTs**: *S. papillosum* (1160 ± 275 mg CO_2-e m^{-2} d^{-1}) < *E. vaginatum* (2536 ± 275mg CO_2-e m^{-2} d^{-1}) < *C. vulgaris* (3894 ± 275 mg CO_2-e m^{-2} d^{-1}) ($F = 22.9$, $p < 0.0001$). **All of the GWP values for the inter-grip mesocosms were positive, indicating radiative forcing or warming** (under CL1; CL2 is considered in section 3.2.3).

Table 3.7. *Steady mean CH_4 flux (mg CH_4 m^{-2} d^{-1}, g CH_4 m^{-2} y^{-1}), NEE (mg CO_2 m^{-2} d^{-1}, g CO_2 m^{-2} y^{-1}), and global warming potential (g CO_2-e m^{-2} y^{-1}) for the three plant functional types under CL1 and CL2 (n =27). Episodic ebullition did not occur. Positive fluxes indicate emission, and negative indicate uptake. Parentheses show standard error. All fluxes are for the period prior to the sulphate amendment being added (week 17; summer-time conditions).*

Climate	**Plant functional type**	Steady CH_4 flux (mg CH_4 m^{-2} d^{-1})	Steady CH_4 flux (g CH_4 m^{-2} y^{-1})	NEE (mg CO_2 m^{-2} d^{-1})	NEE (g CO_2 m^{-2} y^{-1})	GWP (g CO_2 m^{-2} y^{-1})
CL1	*S. papillosum* (Papillose Bog-moss)	49.5 (± 23.3)	**18.1 (± 8.51)**	2088 (± 797)	**762 (± 291)**	1213 (± 317)
	E. vaginatum (Hare's Tail Cotton Grass)	205 (± 23.3)	**74.9 (± 8.51)**	2389 (± 797)	**872 (± 291)**	2745 (± 317)
	C. vulgaris (Common Heather)	120 (± 23.3)	**43.9 (± 8.51)**	4813 (± 797)	**1757 (± 291)**	2853 (± 317)
CL2	*S. papillosum* (Papillose Bog-moss)	86.8 (± 23.3)	**31.7 (± 8.51)**	860 (± 797)	**314 (± 291)**	1106 (± 317)
	E. vaginatum (Hare's Tail Cotton Grass)	294 (± 23.3)	**107 (± 8.51)**	-974 (± 797)	**-356 (± 291)**	2326 (± 317)
	C. vulgaris (Common Heather)	292 (± 23.3)	**106 (± 8.51)**	6230 (± 797)	**2274 (± 291)**	4934 (± 317)

Note: the data in the bolded columns are effectively the same as those in the columns to their immediate left. The mean daily fluxes represent means for the duration of the experiment prior to the sulphate amendment being applied (i.e., four-months' worth of data). For the bolded columns, these means have simply been scaled to a year.

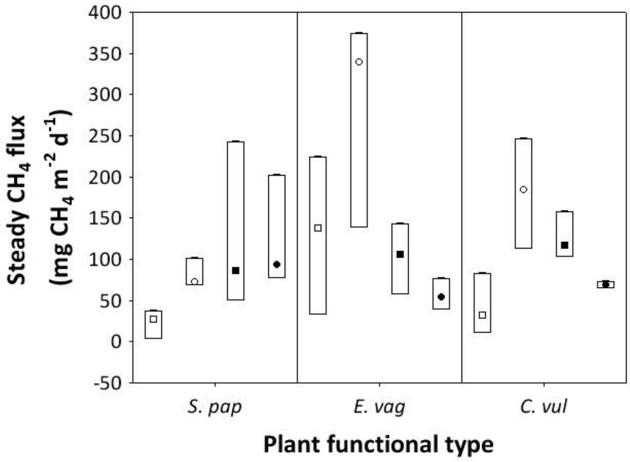

Figure 3.3. *Box plot of seasonal steady CH_4 fluxes from the three plant functional types:* S. papillosum*,* E. vaginatum*, and* C. vulgaris*. Median is represented by the symbol (open square = spring, open circle = summer, closed square = autumn, closed circle = winter), with the box representing the inter-quartile range and the whiskers indicating the full range. Data for S1 cores only.*

Table 3.8 shows the mean pore-water [CH_4] for the three PFTs under CL1 and CL2 for 5- and 15-cm depth (April to July – all mesocosms). It was found that, at a depth of 5 cm, there was a significant difference between *E. vaginatum* (0.68 ± 0.33 mg L^{-1}) and *S. papillosum* (1.71 ± 0.33 mg L^{-1}), whilst *C. vulgaris* was not significantly different from either of the other two PFTs (1.39 ±0.33 mg L^{-1}) (F = 5.97, p = 0.009). In contrast, at a depth of 15 cm there were no significant differences between PFTs (F = 2.55, p = 0.10). Finally, pore-water [CH_4] significantly increased with depth (CL1: F = 27.8, p < 0.0001; CL2: F = 9.16, p = 0.011).

Table 3.9 shows the mean concentrations of base cations, anions, acetate and DOC at 15-cm depth for the three PFTs under CL1 and CL2 (before sulphate amendment applied: all cores). Only DOC differed significantly between PFTs (F = 3.64, p = 0.047; post-hoc: (*S. papillosum* = *C. vulgaris*) < (*C. vulgaris* = *E. vaginatum*)). None of the other pore-water response variables showed statistically-significant differences between PFTs.

Table 3.8. *Mean dissolved [CH_4] at 5- and 15- cm depth for the three PFTs under CL1 and CL2 (*n *= 27). Parentheses show standard error. Data for the period before the sulphate amendment (S1 and S2).*

Climate	Plant functional type	[CH_4] 5 cm (mg L^{-1})	[CH_4] 15 cm (mg L^{-1})
CL1	*S. papillosum*	0.57 (± 0.16)	1.50 (± 0.38)
	E. vaginatum	0.09 (± 0.16)	0.76 (± 0.38)
	C. vulgaris	0.44 (± 0.16)	1.30 (± 0.38)
CL2	*S. papillosum*	0.97 (± 0.23)	1.92 (± 0.54)
	E. vaginatum	0.09 (± 0.23)	0.61 (± 0.54)
	C. vulgaris	0.51 (± 0.23)	1.48 (± 0.54)

3.2.2 Effect of sulphur addition on CH_4 emissions

Hypothesis 7: Sulphate additions will reduce CH_4 fluxes.

Table 3.10 shows the mean steady CH_4 flux expressed in daily and yearly rates (**mg** CH_4 m^{-2} $\mathbf{d^{-1}}$, **g** CH_4 m^{-2} $\mathbf{y^{-1}}$), mean NEE (**mg** CO_2 m^{-2} $\mathbf{d^{-1}}$, **g** CO_2 m^{-2} $\mathbf{y^{-1}}$), and GWP (g CO_2-e m^{-2} y^{-1}) for the three PFTs disaggregated by sulphate amendment application (under the CL1 scenario). It was found that there was no effect of the sulphate amendment on the steady CH_4 flux emission, NEE or GWP (steady CH_4 flux: $F = 0.38$, $p = 0.55$; NEE: $F = 1.51$, $p = 0.24$; GWP: $F = 0.97$, $p = 0.35$). No significant interaction between PFT and sulphate amendment was apparent for any gaseous response variable. On this basis **Hypothesis 7 may be rejected**.

Pore-water [CH_4] was not affected by the sulphate amendment at 5- and 15- cm depth (5 cm: $F = 2.62$, $p = 0.13$; 15 cm: $F = 0.53$, $p = 0.48$) (Table 3.11). However, there were significant differences between PFTs. At 5-cm depth *E. vaginatum* (0.05 ± 0.14 mg L^{-1}) < *C. vulgaris* (0.65 ± 0.14 mg L^{-1}) < *S. papillosum* (1.22 ± 0.14 mg L^{-1}) ($F = 110$, $p < 0.0001$); and at 15-cm depth *E. vaginatum* < *C. vulgaris* = *S. papillosum* ($F = 30.26$, $p < 0.0001$).

Table 3.12 summarises the concentration of cations, anions, acetate and DOC at 15-cm depth disaggregated by PFT and sulphate amendment. It shows that there were significant differences between sulphate amendment treatments for [Na^+], [NH_4^+], [K^+], [Mg^{2+}], [Ca^{2+}] and [SO_4^{2-}]. The S2 mesocosms all had higher concentrations of these response variables (Na^+: $F = 116$, $p < 0.0001$; NH_4^+: $F = 60.2$, $p < 0.0001$; K^+: $F = 18.7$, $p = 0.001$; Mg^{2+}: $F = 9.15$, $p = 0.011$; Ca^{2+}: $F = 5.91$, $p = 0.032$; SO_4^{2-}: $F = 89.9$, $p < 0.0001$).

Hypothesis 8: Warmer conditions will favour CH_4 production and reduce the effect of sulphate additions.

Table 3.13 shows mean steady CH_4 flux expressed in daily and yearly rates (**mg** CH_4 m^{-2} $\mathbf{d^{-1}}$, **g** CH_4 m^{-2} $\mathbf{y^{-1}}$), mean NEE (**mg** CO_2 m^{-2} $\mathbf{d^{-1}}$, **g** CO_2 m^{-2} $\mathbf{y^{-1}}$), and GWP (g CO_2-e m^{-2} y^{-1}) for the three PFTs disaggregated by climate scenario (all sulphate treated cores – S2 mesocosms only, August to December meteorological conditions). Mean steady CH_4 flux was significantly larger ($F = 13.6$, $p = 0.003$) under CL2 (204 ± 17.0 mg CH_4 m^{-2} d^{-1}) compared to CL1 (115 ± 17.0 mg CH_4 m^{-2} d^{-1}). The first part of Hypothesis 8 may therefore be accepted, but, because there was no effect of sulphate on methane emissions (Hypothesis 7), **Hypothesis 8, in its entirety, should be rejected**. NEE and GWP were not significantly different between CL1 and CL2 for the three PFTs ($F = 0.42$, $p = 0.53$, $F = 1.31$, $p = 0.28$, respectively).

Pore-water [CH_4] at 5- and 15- cm depth after the sulphate application was not affected by climate (5 cm: $F = 0.11$, $p = 0.75$; 15 cm: $F = 0.51$, $p = 0.49$) (see Table 3.14). Table 3.15 summarises the concentration of cations, anions, acetate and DOC at 15 cm depth disaggregated by PFT and climate after sulphate application (August to December). It shows that there were no significant differences between sulphate amendment treatments for any of the pore-water response variables.

3.2.3 Effect of climate on CH_4 emissions

Hypothesis 9: A warmer climate will lead to higher rates of CH_4 emission.

It was found that there is a higher mean steady CH_4 flux under CL2 (224 ± 19.0 mg CH_4 m^{-2} d^{-1}) than CL1 (125 ± 13.5 mg CH_4 m^{-2} d^{-1}) ($F = 5.81$, $p = 0.03$) (Table 3.7). **Therefore, Hypothesis 9 may be accepted**. No such effect was apparent for NEE and GWP (NEE: $F = 3.18$, $p = 0.09$; GWP: $F = 0.37$, $p = 0.55$). It is interesting to note that NEE for *E. vaginatum* was higher under CL1 (-1319 ± 1538 mg CO_2m^{-1} d^{-1}) than for CL2 (-5101 ± 1538 mg CO_2m^{-1} d^{-1}), suggesting that CO_2 uptake is enhanced under the warmer climate scenario. However, the net CO_2 uptake was insufficient to offset the CH_4 release (GWP was positive: Table 3.7). The concentration of pore-water CH_4, cations, anions, acetate and DOC were not influenced by climate scenario.

Table 3.9. *Mean concentrations (in mg L^{-1}) of base cations, anions, acetate and DOC at 15cm depth for the three management types under CL1 and CL2 (*n = 27*). Parentheses show standard error. All cores pre-sulphate amendment (S1 and S2).*

Climate	Plant functional type	$[Na^+]$	$[NH_4^+]$	$[K^+]$	$[Mg^{2+}]$	$[Ca^{2+}]$	$[Cl^-]$	$[PO_4^{3-}]$	$[NO_3^-]$	$[SO_4^{2-}]$	[Acetate]	[DOC]
CL1	*S. papillosum*	11.5 (±2.68)	2.29 (±1.41)	5.52 (±1.96)	1.54 (±0.65)	2.04 (±0.60)	10.3 (±0.73)	2.26 (±2.38)	0.93 (±0.35	2.19 (±0.49)	17.4 (±8.59)	50.2 (±23.9)
	E. vaginatum	18.1 (±2.68)	4.67 (±1.41)	5.70 (±1.96)	3.14 (±0.65)	3.88 (±0.60)	11.1 (±0.73)	8.52 (±2.38)	1.54 (±0.35)	2.48 (±0.49)	34.1 (±8.59)	133 (±23.9)
	C. vulgaris	14.1 (±3.29)	2.78 (±1.72)	5.85 (±2.40)	2.80 (±0.80)	3.21 (±0.74)	12.4 (±0.90)	5.66 (±2.92)	0.71 (±0.43)	1.80 (±0.59)	29.1 (±10.5)	98.4 (±29.2)
Cl2	*S. papillosum*	14.4 (±3.80)	4.00 (±1.99)	9.15 (±2.77)	2.87 (±0.92)	3.64 (±0.85)	11.5 (±1.03)	4.39 (±3.37)	0.57 (±0.49)	4.20 (±0.69)	17.7 (±12.2)	50.1 (±33.7)
	E. vaginatum	14.6 (±3.80)	2.22 (±1.99)	4.83 (±2.77)	4.19 (±0.92)	3.84 (±0.85)	13.7 (±1.03)	4.14 (±3.37)	0.63 (±0.49)	2.37 (±0.69)	25.7 (±12.2)	127 (±33.7)
	C. vulgaris	12.3 (±4.65)	2.54 (±2.44)	5.77 (±3.40)	2.58 (±1.13)	3.27 (±1.13)	11.9 (±1.27)	6.20 (±4.13)	0.97 (±0.60)	2.02 (±0.84)	13.4 (±14.9)	54.4 (±41.3)

Table 3.10. *Steady mean CH_4 flux (mg CH_4 m^{-2} d^{-1}, g CH_4 m^{-2} y^{-1}), NEE (mg CO_2 m^{-2} d^{-1}, g CO_2 m^{-2} y^{-1}), and global warming potential (g CO_2-e m^{-2} y^{-1}) for the three plant functional types with sulphate amendment (S1 and S2), under CL1 (n = 18). Positive fluxes indicate emission, and negative indicate uptake. Parentheses show standard error. Based on data from all cores post-sulphate amendment (S1 and S2) for the CL1 scenario.*

Sulphate amendment	**Plant functional type**	Steady CH_4 flux (mg CH_4 m^{-2} d^{-1})	Steady CH_4 flux (g CH_4 m^{-2} y^{-1})	NEE (mg CO_2 m^{-2} d^{-1})	NEE (g CO_2 m^{-2} y^{-1})	GWP (g CO_2 m_{-2} y^{-1})
S1	*S. papillosum*	117 (±38.0)	**42.8 (±13.9)**	966 (±1538)	**352 (±561)**	1422 (±756)
	E. vaginatum	134 (±38.0)	**48.8 (±13.9)**	-1319 (±1538)	**-481 (±561)**	737 (±756)
	C. vulgaris	137 (±38.0)	**50.2 (±13.9)**	3622 (±1538)	**1322 (±561)**	2576 (±756)
S2	*S. papillosum*	124 (±38.0)	**45.1 (±13.9)**	376 (±1538)	**137 (±561)**	1264 (±756)
	E. vaginatum	142 (±38.0)	**51.7 (±13.9)**	-5101 (±1538)	**-1862 (±561)**	-571 (±756)
	C. vulgaris	109 (±38.0)	**39.8 (±13.9)**	3360 (±1538)	**1226 (±561)**	2220 (±756)

Note: the data in the bolded columns are effectively the same as those in the columns to their immediate left. The mean daily fluxes represent means for the duration of the experiment after the sulphate amendment being applied (i.e., five-months' worth of data). For the bolded columns, these means have simply been scaled to a year.

Table 3.11. *Mean pore-water [CH_4] at 5- and 15- cm depth for the three plant functional types under S1 and S2 (*n *= 18). Parentheses state standard error. Based on data from all cores post-sulphate amendment (August to December meteorological conditions) for the CL1 scenario.*

Sulphate amendment	**Plant functional type**	[CH_4] 5 cm (mg L^{-1})	[CH_4] 15 cm (mg L^{-1})
S1	*S. papillosum*	0.84 (± 0.20)	3.83 (± 0.77)
	E. vaginatum	0.06 (± 0.20)	0.22 (± 0.77)
	C. vulgaris	0.50 (± 0.20)	1.65 (± 0.77)
S2	*S. papillosum*	1.60 (± 0.20)	2.13 (± 0.77)
	E. vaginatum	0.04 (± 0.20)	0.13 (± 0.77)
	C. vulgaris	0.80 (± 0.20)	2.30 (± 0.77)

Table 3.12. *Mean concentrations (in mg L^{-1}) of base cations, anions, acetate and DOC at 15-cm depth for the three plant functional types under S1 and S2 (*n *= 18). Parentheses show standard error. Based on data from all cores post-sulphate amendment (August to December meteorological conditions) for the CL1 scenario.*

Sulphate amendment	**Plant functional type**	[Na^+]	[NH_4^+]	[K^+]	[Mg^{2+}]	[Ca^{2+}]	[Cl^-]	[PO_4^{3-}]	[NO_3^-]	[SO_4^{2-}]	[Acetate]	[DOC]
S1	*S. papillosum*	9.70 (±1.82)	1.61 (±0.31)	2.84 (±0.48)	0.72 (±0.36)	2.08 (±0.49)	9.13 (±1.20)	0.47 ±0.98)	0.60 (±0.34)	1.56 (±3.53)	3.04 (±5.32)	24.2 (±16.6)
	E. vaginatum	14.9 (±1.82)	1.71 (±0.31)	1.40 ±0.48)	1.68 (±0.36)	2.85 (±0.49)	13.2 (±1.20)	0.44 (±0.98)	0.97 (±0.34)	2.26 (±3.53)	0.16 (±5.32)	50.9 (±16.6)
	C. vulgaris	16.9 (±1.82)	0.90 (±0.31)	1.47 (±0.48)	2.84 (±0.36)	4.68 (±0.49)	13.3 (±1.20)	1.76 (±0.98)	1.01 (±0.34)	4.75 (±3.53)	5.68 (±5.32)	96.0 (±16.6)
S2	*S. papillosum*	29.0 (±1.82)	4.58 (±0.31)	5.42 (±0.48)	2.57 (±0.36)	3.10 (±0.49)	12.0 (±1.20)	0.98 (±0.98)	1.89 (±0.34)	38.5 (±3.53)	12.8 (±5.32)	73.7 (±16.6)
	E. vaginatum	28.2 (±1.82)	2.17 ±0.31)	1.38 (±0.48)	2.48 (±0.36)	4.23 (±0.49)	13.3 (±1.20)	0.06 (±0.98)	0.75 (±0.34)	28.3 (±3.53)	0.16 (±5.32)	63.8 (±16.6)
	C. vulgaris	32.6 (±1.82)	3.28 (±0.31)	3.98 (±0.48)	2.89 (±0.36)	5.20 (±0.49)	13.3 (±1.20)	5.14 (±0.98)	0.79 (±0.34)	23.9 (±3.53)	18.9 (±5.32)	113 (±16.6)

Table 3.13. *Steady mean CH_4 flux (mg CH_4 m^{-2} d^{-1}, g CH_4 m^{-2} y^{-1}), NEE (mg CO_2 m^{-2} d^{-1}, g CO_2 m^{-2} y^{-1}), and global warming potential (g CO_2-e m^{-2} y^{-1}) for the three plant functional types treated with sulphate (S2-only), under CL1 and CL2 (n =18). Positive fluxes indicate emission, and negative indicate uptake. Parentheses show standard error. Based on data from S2 cores post-sulphate amendment (August to December meteorological conditions).*

Climate	Plant functional type	Steady CH_4 flux (mg CH_4 m^{-2} d^{-1})	Steady CH_4 flux (g CH_4 m^{-2} y^{-1})	NEE (mg CO_2 m^{-2} d^{-1})	NEE (g CO_2 m^{-2} y^{-1})	GWP (g CO_2 m_{-2} y^{-1})
CL1	*S. papillosum*	124 (± 49.5)	**45.1 (± 8.1)**	376 (± 1606)	**137 (± 586)**	1264 (± 946)
	E. vaginatum	142 (± 49.5)	**51.7 (± 8.1)**	-5101 (± 1606)	**-1862 (± 586)**	-571 (± 946)
	C. vulgaris	109 (± 49.5)	**39.8 (± 8.1)**	3360 (± 1606)	**1226 (± 586)**	2220 (± 946)
CL2	*S. papillosum*	88.3 (± 49.5)	**32.2 (± 8.1)**	540 (± 1606)	**197 (± 586)**	1003 (± 946)
	E. vaginatum	218 (± 49.5)	**79.6 (± 8.1)**	-6692 ± 1606)	**-2443 (± 586)**	-452 (± 946)
	C. vulgaris	257 (± 49.5)	**93.7 (±18.1)**	7320 (± 1606)	**2672 (± 586)**	5013 (± 946)

Note: the data in the bolded columns are effectively the same as those in the columns to their immediate left. The mean daily fluxes represent means for the duration of the experiment after the sulphate amendment being applied (i.e., five-months' worth of data). For the bolded columns, these means have simply been scaled to a year.

Table 3.14. *Mean dissolved [CH_4] at 5 and 15cm depth for the three plant functional types under CL1 and CL2 (n = 18). Parentheses state standard error. Based on data from after the sulphate amendment (S2 only).*

Climate	Plant functional type	[CH_4] 5 cm (mg L^{-1})	[CH_4] 15 cm (mg L^{-1})
CL1	*S. papillosum*	1.60 (± 0.34)	2.13 (± 0.79)
	E. vaginatum	0.04 (± 0.34)	0.13 (± 0.79)
	C. vulgaris	0.80 (± 0.34)	2.30 (± 0.79)
CL2	*S. papillosum*	1.09 (± 0.34)	2.67 (± 0.79)
	E. vaginatum	0.04 (± 0.34)	0.46 (± 0.79)
	C. vulgaris	1.04 (± 0.34)	2.82 (± 0.79)

Table 3.15. *Mean concentrations of base cations, anions, acetate and DOC at 15cm depth for the three management types under CL1 and CL2 (n = 18). Parentheses state standard error. Based on data from all cores post-sulphate amendment (August to December conditions) for all sulphate amended cores (S2 only).*

Climate	Plant functional type	[Na^+]	[NH_4^+]	[K^+]	[Mg^{2+}]	[Ca^{2+}]	[Cl^-]	[PO_4^{3-}]	[NO_3^-]	[SO_4^{2-}]	[Acetate]	[DOC]
CL1	*S. papillosum*	29.0 (±2.72)	4.58 (±0.52)	5.42 (±0.61)	2.57 (±0.39)	3.10 (±0.36)	12.0 (±0.95)	0.98 (±1.16)	1.89 (±0.31)	38.5 (±3.90)	12.8 (±5.88)	73.7 (±11.9)
	E. vaginatum	28.2 (±2.72)	2.17 (±0.52)	1.38 (±0.61)	2.48 (±0.39)	4.23 (±0.36)	13.3 (±0.95)	0.06 (±1.16)	0.75 (±0.31)	28.3 (±3.90)	0.16 (±5.88)	63.8 (±11.9)
	C. vulgaris	32.6 (±2.72)	3.28 (±0.52)	3.98 (±0.61)	2.89 (±0.39)	5.20 (±0.36)	13.3 (±0.95)	5.14 (±1.16)	0.79 (±0.31)	23.9 (±3.90)	18.9 (±5.88)	113 (±11.9)
CL2	*S. papillosum*	28.2 (±2.72)	4.05 (±0.52)	3.84 (±0.61)	1.68 (±0.39)	2.30 (±0.36)	12.7 (±0.95)	1.53 (±1.16)	1.03 (±0.31)	29.4 (±3.90)	2.50 (±5.88)	50.5 (±11.9)
	E. vaginatum	37.2 (±2.72)	1.43 (±0.52)	0.98 (±0.61)	3.06 (±0.39)	4.49 (±0.36)	19.0 (±0.95)	0.57 (±1.16)	0.91 (±0.31)	29.7 (±3.90)	0.25 (±5.88)	85.7 (±11.9)
	C. vulgaris	36.2 (±3.33)	3.92 (±0.63)	3.93 (±0.75)	2.73 (±0.47)	3.85 (±0.45)	15.1 (±1.16)	9.72 (±1.42)	0.92 (±0.38)	26.5 (±4.77)	10.5 (±7.20)	78.5 (±14.6)

4. Discussion

4.1 *Effect of restoration (infill) on blocked/dammed grip CH_4 emissions*

CH_4 emissions differed according to the grip-blocking method. Re-profiling, heather bale, and *Sphagnum* mat had significantly higher emissions than the no-infill mesocosms, with the latter showing no net release of CH_4 or even a slight uptake. It is interesting that the *Sphagnum* mat cores had emissions that were as high as the other infill materials, which appears to be contrary to the measurements of **Frenzel and Karofeld (2000)** that hollow Sphagna can oxidise nearly all of the CH_4 travelling upwards through the peat profile. It is possible that the *Sphagnum* mats were intensely oxidising but that production deeper in the profile was commensurately higher. There is some evidence of high production in these cores in that pore-water [CH_4] at 15-cm depth was substantially higher (more than an order of magnitude) in the *Sphagnum* mesocosms than in any other type. Despite this evidence, it is also possible that not all *Sphagnum* mats are as oxidising as suggested by the study of **Frenzel and Karolfeld (2000)**. The lack of CH_4 emission from the no-infill cores may not be that realistic. In the field, the pools behind the dams might be expected to receive DOC from surrounding peat (this is likely to be the case for infilled grips too because such grips usually remain as local depressions or sinks, thus receiving water from surrounding peat). This situation of the pools receiving water was one we could not easily replicate in the laboratory. Any DOC-rich water entering pools in the field may be 'processed' to form CH_4 (and also CO_2) if the dark DOC-rich water in pools causes them to warm, so speeding up decomposition rates. Further, photo-degradation of DOC may occur in pools (e.g., **Waiser and Robarts. 2004**), providing readily-decomposable substrate for methanogens.

CH_4 emissions from the re-profiling mesocosms were initially comparable with the no-infill cores (during the simulated spring conditions). However, as plants established in these cores, CH_4 emissions increased substantially (an increase from a mean of 3.37 mg CH_4 m^{-2} d^{-1} in spring to 60.2 mg CH_4 m^{-2} d^{-1} in winter; see also Figure 3.2). Much of this increase in emissions may be due to the establishment of the sedge *E. vaginatum* in these cores (Figure 3.1 shows three tillers of *E. vaginatum* growing nine months after an initial condition of bare peat). Similar findings have been reported in the literature. For example, **Waddington and Day (2007)** reported increasing CH_4 emissions at the Bois des Bel peatland (Quebec, Canada) with the establishment of vegetation after restoration: average growing-season emissions increased from 0.6 to 34.7 mg CH_4 m^{-2} d^{-1} during the first three years post-restoration (see also **Baird *et al*., 2009**).

All GWP (expressed for a 100-year time frame) for the in-grip restoration outcomes were positive, indicating a net radiative forcing (warming) effect. Although this finding appears to suggest that restoration is not achieving its aim, it is important to note that there was **no comparison with the 'do-nothing' scenario where grips would be left as active drains**. It is possible that the GWP of the un-restored case would have been higher than for the different types of restoration method. It is also important to note that **our data relate only to the immediate post-restoration period**. Plant growth may have been inhibited by the higher water tables, and it is unlikely the mesocosms adjusted fully to the new conditions. For example, one might expect the pattern of root growth to change following wetting, with deeper roots dying and starting to decompose. Similarly, over a few years one might expect a change in plant species composition or relative abundance (i.e., plant succession). The field trials will provide data on how active grips compare with dammed and dammed and in-filled grips, and on how fluxes change over a longer post-restoration period, thus providing a fuller picture than is possible here.

GWP was significantly higher for the heather bale treatments than the three other management types. Heather bale had a high NEE (1707 ±231 g CO_2 m^{-2} y^{-1} for CL1), which suggests intense decomposition of the heather was occurring within the cores (supported by the higher pore-water [DOC] in heather-bale cores). High NEE and GWP (similar magnitudes to those observed in this study) have been observed in restored Canadian cutover bogs, where straw mulches have been used (**Höper *et al*., 2008**) (**see also Baird et al., 2009**). Although such high NEE values might be expected to be relatively short-lived (5-10 years), and although heather will re-grow in areas harvested for grip infill (thus offsetting these high NEEs), a reduction in NEE would coincide with the final stages in the decomposition and break-up of the heather, which could lead to grip dams failing, an obviously undesirable outcome. **In terms of GWP, damming without infilling**

and thereafter a transition to *Sphagnum* mats would appear to give the best restoration outcome (see Table 3.1).

Episodic ebullition was confined to April- and May- time conditions and represented a very small fraction of overall CH_4 emissions (Table 3.1). Some studies have suggested that ebullition is an important component (>> 10 %) of total CH_4 fluxes (see the review in **Coulthard *et al*., 2009**), with its contribution greatest during the passage of low-pressure weather systems which seem to trigger bubble release (e.g., **Tokida *et al*., 2005**). It is not clear why ebullition was so low in our cores, but similar findings have been observed recently by **Green and Baird (in press)** and **Green and Baird (in review)**. The episodic ebullition data were consistent with the pore-water [CH_4] data, with highest rates of ebullition coinciding with the highest pore-water [CH_4] (in the *Sphagnum*-mat mesocosms – see Table 3.1 and Table 3.2).

4.2 *Effect of water level on GHG emissions*

As noted in section 1.2.2, there are good reasons for expecting CH_4 emissions from peatlands to be affected by water-level (water-table) regime. Contrary to these expectations, **water-table regime had no significant effect on CH_4 emissions**; neither did it have an effect on pore-water [CH_4] at either the 5- or 15- cm depth. Although NEE was significantly higher under a constant water table (WL1) (2177 ± 181 mg CO_2 m^{-2} d^{-1}) than a variable water table (WL2) (1620 ± 181 mg CO_2 m^{-2} d^{-1}), the difference was insufficient to cause a significant difference in GWP between water-table regimes. It is unclear why water-level regime did not have a greater effect on GHG fluxes. Decomposition of litter and peat tends to be much higher under oxic than anoxic conditions (e.g., **Moore *et al*., 2007**), and decomposition during oxic conditions may provide substrate for methanogens after a return to anoxia (higher water tables). If this were the case, and if methanotrophy was not greatly enhanced during periods of lower water tables, then it could explain why total fluxes of CH_4 from the WP2 mesocosms were not significantly different (lower) than those from the WP1 mesocosms. It is also possible that the variation in water-table between treatments was simply insufficient to have an impact on CH_4 dynamics.

4.3 *Effect of climate on emissions*

There was no effect of a warmer climate on CH_4, NEE or GWP in the different restoration outcomes assessed in Experiment 1 (Hypothesis 5). CH_4 fluxes from the inter-grip areas (Experiment 2) were affected by climate, with CH_4 emissions 78 % higher under the future climate scenario (CL2) (see Table 3.7). However, the NEE and GWP data showed that the 2°C temperature increase had no net effect in terms of radiative forcing. It should be noted that CL2 only considers an elevated temperature scenario; other meteorological variables were not included in the assessment. Studies on how changes in rainfall and drought regime affect GHG fluxes from peatlands would be useful.

4.4 *Effect of vegetation on CH_4 emissions from inter-grip areas*

Numerous studies have shown that sedges are associated with higher rates of CH_4 emission (compared to areas without sedges and dominated by *Sphagnum*) (e.g. **Whiting and Chanton, 1992**; **Waddington *et al.*, 1996**; **Green and Baird, in press**). Our results similarly show that sedges are associated with higher mean CH_4 emissions, with the *S. papillosum* mesocosms (68.1 ± 20.2 mg CH_4 m^{-2} d^{-1}) having a significantly lower CH_4 flux than the *C. vulgaris* (206 ± 20.2 mg CH_4 m^{-2} d^{-1}) and *E. vaginatum* (250 ± 20.2 mg CH_4 m^{-2} d^{-1}) cores. Dissolved [CH_4] was also lower in the *E. vaginatum* mesocosms than in the *S. papillosum* samples, which is consistent with findings in other studies (**Chanton, 2005**; **Green and Baird, in press**). There are several possible reasons for the higher fluxes from sedges as outlined in the rationale for Hypothesis 6 (section 1.3.1).

An important question, however, is whether the differences in CH_4 fluxes translate into significant differences in terms of GWP. All GWPs were positive (NEE was insufficient to offset CH_4 emissions, and net CO_2 uptake was only apparent for *E. vaginatum*), indicating a positive radiative forcing (net warming effect) in the first year after restoration (under CL1). GWP was lowest for *S. papillosum*, and so management practices that promote *S. papillosum* over other PFTs (e.g., grazing) may help to produce the best outcome in terms of radiative impact. As noted above in section 3.1.1, we did not consider a no-restoration treatment in the laboratory experiments. However, the field experiments will be able to provide a comparison between restored and un-restored treatments.

4.5 *Effect of sulphur addition on CH_4 emissions*

A number of studies suggest that sulphate additions reduce peatland and, more generally, wetland CH_4 emissions (e.g., **Gauci *et al*., 2002, 2004a, 2005, 2006**). It is thought that sulphate stimulates competitive interactions with sulphate-reducing bacteria (SRB) that are energetically superior to methanogens, thus leading to lower CH_4 fluxes where biologically-available C substrate is limiting (as is the case in peatlands). Sulphate acts as an inorganic electron acceptor and therefore diverts substrate away from methanogenesis, thereby reducing CH_4 flux to the atmosphere. The majority of nutrient input in ombrotrophic peatlands is via atmospheric deposition; concentrations of NO_3^- and oxidised Mn and Fe are generally low and do not contribute substantially to anaerobic C mineralisation. Decomposition is, therefore, usually dominated by fermenters that break down labile organic compounds to acetate, other simple organic compounds, and hydrogen. H_2/CO_2 reduction is the dominant methanogenesis pathway in ombrotrophic peatlands. There are numerous studies (field and laboratory) that have investigated the impact of SO_4^{2-} deposition (10 to 150 kg S ha^{-1} yr^{-1}), applied as either a single dose or in small, regular, pulses that mimic precipitation, on CH_4 emissions and/or sulphate reduction rates (e.g., **Dise and Verry, 2001**; **Fowler *et al*., 1995**; **Gauci *et al*., 2002, 2004a**; **Vile *et al*., 2003**; **Watson and Nedwell, 1998**). All have shown suppression in CH_4 emissions of up to 50% compared to control cores and sites, in response to low levels of sulphate deposition in the range that is representative of that experienced across Europe.

In Experiment 2 no effect of sulphate on CH_4 emissions was observed for any of the three PFTs. The peat samples used for the laboratory experiments were taken from an area with active grip drainage, so that the laboratory water-table settings would likely have been higher than those experienced in the field. Prior to the laboratory experiments, the peat in the samples would have experienced sustained low water tables as a consequence of grip drainage (the grips at the field site were dug more than 20 years ago – Trystan Edwards, National Trust, pers. comm.). During that period of sustained drainage, any reduced S compounds that formed prior to drainage would have been re-oxidised (see **Gauci *et al*.,2002**). In addition, **Freeman *et al*. (1994)** and **Dowrick *et al*. (2006)** have reported that sulphate accumulation occurs under drought conditions, which they suggest suppresses CH_4 emissions after rewetting. A similar effect could explain our data.

All mesocosms used for Experiment 2 had a substantial pore-water sulphate concentration (Tables 3.9, 3.12, 3.15) even at the beginning of the experiment, and it is likely that this sulphate was sufficient to suppress CH_4 emissions, even within the control (S1) mesocosms (no sulphate addition), resulting in no significant difference between the S1 (no sulphate) and the S2 (sulphate added) treatments. However, the suppressive sulphate already present in the peat can decline after re-wetting as some of the sulphur slowly moves into forms that play little biological role (e.g., carbon-bonded sulphur), and it is likely that areas not receiving additional sulphate will eventually show increases in CH_4 emissions compared to areas receiving additional sulphate application, as the active sulphate pool diminishes. The duration of this 'recovery' from sulphate suppression is not clear but it may extend over decades **(Gauci *et al*. 2005)**. Long-term field experiments are therefore required to assess the benefits and most appropriate timing of using direct application of alternative electron acceptors such as sulphate as a GWP mitigation strategy.

Temperature is also thought to have an effect on sulphate-related suppression of CH_4 emissions. For example, **Gauci *et al*. (2002, 2004a)** showed that CH_4 production was further suppressed by SO_4^{2-} during cooler periods of the year, which suggests that competition between methanogens and sulphate-reducing bacteria for substrate is temperature-dependent. In this study, the steady CH_4 fluxes were substantially lower under present-day conditions (115 ± 17.0 mg CH_4 m^{-2} d^{-1}) (CL1) compared to the possible future scenario (204 ± 17.0 mg CH_4 m^{-2} d^{-1}) (CL2) (Table 3.13), supporting the previous work showing temperature-dependency. However, NEE and GWP (over a 100 year time-frame) were unaffected by climate.

5. Conclusions and executive summary

The overall aim of project SP1202 is to provide information which can be used to identify blanket peatland restoration methods yielding the lowest GWP. The laboratory mesocosm study has proved useful in revealing how restoration method and plant functional type affect GHG fluxes in both grips and inter-grip areas. The laboratory findings are, in some senses, provisional; the experiments considered only a short period after restoration in the somewhat artificial conditions of an environmental cabinet. Although a fuller picture will be available after the conclusion of the field experiments (end of project), at this stage in the project it does seem clear that:

- The method of grip blocking/damming does make a difference with respect to CH_4 emissions and GWP. Of the methods or outcomes considered, it seems that damming with no infill between the dams is preferred to either of the methods involving infilling (heather bale and re-profiling). Open water colonised by *Sphagnum* had a similar outcome in terms of GWP to open water, and might be regarded as preferable to the latter for a variety of reasons (aesthetic, biodiversity (number of *Sphagnum* species)).

- The GWP of all within-grip restoration outcomes was positive (i.e., indicating a net warming effect), and was not influenced by climate or water-table regime. It would be interesting to see how the restoration methods compare with the do-nothing scenario (grips left as active drains) in the longer-term field trials.

- Plant functional type influences CH_4 and GWP in restored blanket bog, with the *Sphagnum* PFT (*S. papillosum*) having a lower radiative forcing than the ericaceous shrub and sedge PFTs (*C. vulgaris* and *E. vaginatum*). **This finding suggests that efforts should be made to encourage *Sphagnum* spread in restored areas.**

- GWP is positive for all plant functional types shortly after re-wetting, and is influenced by climate.

- There is no short-term suppressive influence of sulphate amendments on CH_4 emissions from restored blanket bog, possibly because of prior sustained lower water tables resulting in a build-up of sulphate from re-oxidised reduced S compounds. There may yet be a long-term effect of sulphate applications on CH_4 emissions.

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